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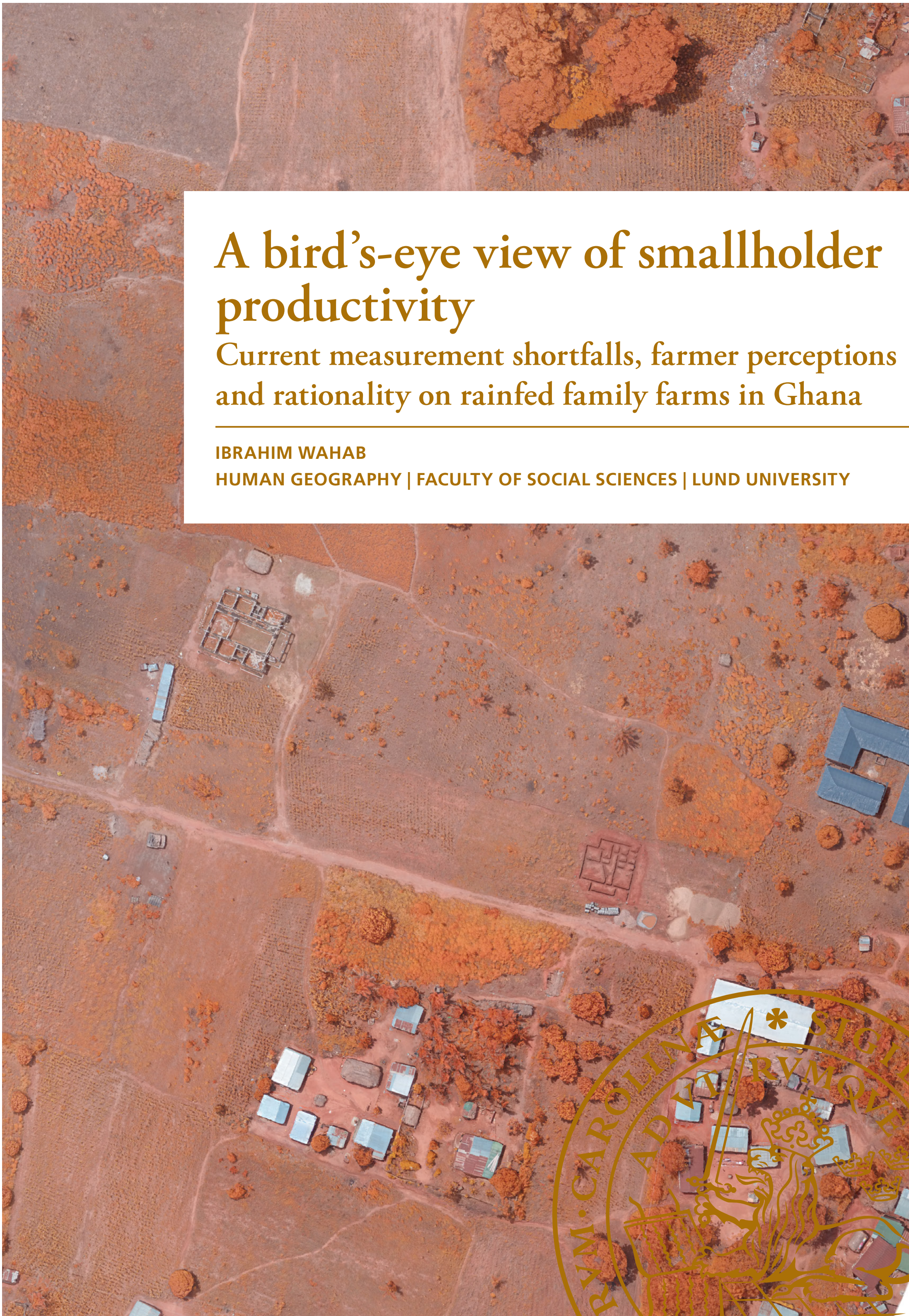
Wahab, Ibrahim



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IBRAHIM WAHAB

HUMAN GEOGRAPHY | FACULTY OF SOCIAL SCIENCES | LUND UNIVERSITY

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Title and subtitle
A bird's eye-view of smallholder productivity: Current measurement shortfalls, farmer perceptions and rationality on rainfed family farms in Ghana

Abstract
Smallholder farming, which is largely rainfed and relies on mostly rudimentary tools, predominates Ghana's agricultural sector. The sector's importance to the national economy is exemplified in not only the proportion of the active national labour force engaged in it but also in terms of its export earnings and service as a source of food for the vast majority of the population. However, the sectors is also plagued with historically low productivity. Statistics from the country's national statistical service shows that while more than six tons per hectare is achievable for maize, what farmers actually obtain from their plots is less than a third of this. Being the most important staple crop and given the continuously increasing population growth rate, these low yield levels are most worrying. This is particularly so if the agriculture sector is expected to play the historically important role of being the engine of economic growth for the national economy as it has been for other countries.

Through this thesis, I aim to augment our present understanding of crop productivity levels on smallholder family farms. I do this by showing the limitations of current methods of yield measurement, analysing the factors contributing to current yield levels and variability, as well as analysing farmers' perspectives on their current productivity levels. Using a multidisciplinary framework, I employ a mixed methods approach to analyse data from field and household surveys as well as aerial photographs and photo-elicitation interviews. For inspiration, I also draw on a number of theories; Boserup's theory on agricultural intensification in the face of population growth and Chayanov's theory of the smallholder economy help provide the frame for the thesis. The more practical induced innovation model of agricultural development and the sustainable livelihood approach help provide the bridge to the empirical work.

The thesis comprises four articles, which are preceded by a kappa. I argue that current measurement approaches do not adequately capture the dynamism of smallholder farms and that the use of new remote sensing tools as employed in this work could be critical to improving the reliability of agricultural statistics in such complex farming systems. I also argue that the factors contributing to current yield levels are varied and inconsistent across yield measures and villages even in the same agroecological regions. I further argue that while management activities such as the timing of planting and quantity of fertilizer applied are important immediate determinants of yield levels, they are often underpinned by some socioeconomic factors relating to labour and land tenure dynamics. The thesis further establishes that, by and large, farmers are content with current productivity levels and this attitude is rationally based on their experience and knowledge of poorly functioning agricultural inputs and outputs market. These findings have significant implications for the future of these small farms in terms of their own survival as well as their ability to continue to play critical roles in the economies of developing countries in Sub-Saharan Africa.

Key words
Smallholder productivity, measurement shortfalls, maize yield levels, aerial photos, farmer attitudes, Ghana

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Thank you all!

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Ibrahim Wahab

Accra, March 2020.

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MADE IN SWEDEN

Dedicated to my wife, Esther and our children, Eli and Zach!

Be ashamed to die until you have scored some victory for humanity
– Neil deGrasse Tyson, June 2020

Table of Contents

List of Articles

Article I

Wahab, I., Hall, O. and Jirström, M. (2018). Remote sensing of yields: Application of UAV-derived NDVI for estimating maize vigour and yields in complex smallholder farming systems in Sub-Saharan Africa. *Drones, 2*(3), 28. doi:https://doi.org/10.3390/drones2030028.

Article II

Wahab, I. (2019). In-season plot area loss and implications for yield estimation in smallholder rainfed farming systems at the village level. *GeoJournal, 2019*. https://doi.org/10.1007/s10708-019-10039-9.

Article III

Wahab, I., Jirström, M., and Hall, O. (2020). An integrated approach to unravelling smallholder yield levels: The case of maize family farms, Eastern Region, Ghana. *Agriculture, 10(6).* https://doi.org/10.3390/agriculture10060206.

Article IV

Wahab, I., Hall, O., and Jirström, M. *(Submitted to a peer-reviewed journal)* Smallholder farmer perceptions and attitudes to yield variability on maize plots in the Eastern Region of Ghana.

List of Figures

List of Acronyms

DAO	District Agriculture Officer
FAO	Food and Agriculture Organization
FAW	Fall Army Worm
GCS	Ground Control Station
GDP	Gross Domestic Product
GLSS	Ghana Living Standards Survey
gNDVI	Green Normalized Difference Vegetation Index
GPS	Global Positioning System
GSS	Ghana Statistical Service
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
PEI	Photo-Elicitation Interview
RGB	Red, Green, and Blue
SRID-MoFA	Statistics, Research and Information Directorate of the Ministry of Food and Agriculture
SSA	Sub-Saharan Africa
UAV	Unmanned Aerial Vehicle
VFC	Village Farmers' Chief
VTOL	Vertical Take-Off and Landing

1 Introduction to the thesis

> "How to raise productivity among the rural poor in developing countries is one of two or three most urgent questions confronting the international development community today" – Robert S. McNamara, in the foreword to Uma Lele's book: 'The design of rural development: Lessons from Africa' (1975)

1.1 Introduction

The quotation above encapsulates my motivation for writing this thesis. Having grown up in a farming village, I was always driven to pursue education due to the irksomeness of the drudgery associated with traditional agriculture as practised in Worawora, Ghana. The traditional nature of farming is not peculiar to this location; it is the same for much of the country and even the continent. As Binswanger-Mkhize and Savastano (2017) posits, the nature of an agriculture system that evolves and is practised, in terms of level and type of intensification, methods of maintaining soil fertility, and the type of technology employed, is largely influenced not only by agroecological conditions but also the socioeconomic situation that confronts producers. Thus, the kind of farming that obtains in much of Sub-Saharan Africa is dogged by low levels of technology, intensification, and productivity. Despite the passing of more than four decades since its authorship, the quotation above is as relevant today as it was then.

A critical challenge confronting SSA, in contemporary times, is the coexistence of a rapidly growing population and stagnating, and even collapse, of agricultural yields. Poor agricultural productivity has been recognized as an important global problem that needs addressing. Agriculture is still top of the global development agenda given its linkage to a number of the Sustainable Development Goals (SDGs): eradicating poverty (goal 1) and hunger (goal 2), achieving decent work and economic growth (goal 8), reduced inequality (goal 10) and responsible consumption and production (goal 12) (UN, 2019). However, the challenges confronting SSA agriculture are neither amenable to straightforward solutions nor have they garnered the much-needed attention of policy- and decision-making in the countries where they are most acute.

The main difference between the agricultures of developed regions – and including the agricultures of parts of Asia and South America – on the one hand, and developing countries predominantly in SSA, on the other hand, is the level of intensification. This difference leads to substantial disparity in productivity between the two categories of agricultures. So vast is the gap that by the end of the 20th Century, the ratio of gross productivity between SSA and the developed countries stood at 1:2,000 (Mazoyer & Roudart, 2006). One of the underlying causes of the failure of SSA agriculture to keep pace with the rest of the world is its failure to adopt and use technological innovations that characterized the Second Agricultural Revolution, which occurred concurrently with the Industrial Revolution between 1700 and 1900 in developed countries. Similarly, participation in the Third Agricultural Revolution, also termed the Green Revolution, and which began in the middle of the 20th Century, has largely eluded smallholders in SSA.

In the last couple of decades, significant advances in computerization and miniaturization has ushered in a new kind of agricultural revolution: digitization in agriculture (Stern, 2015). This has allowed precision agriculture to be practised and, thus, further enhanced productivity in ‘more advanced’ agricultures but which till date has been nearly impossible to replicate on SSA farms due to relatively small field sizes and complexity of cropping systems. The use of Unmanned Aerial Vehicles (UAVs) in agricultural research in the last decade has reduced some of the barriers to the application of precision agriculture tools in SSA agriculture. The use of such new technologies offers higher resolution remote sensing data which now allows the estimation of crop health as well as shed light on within-field crop vigour variability. This is the central focus of the *first objective* of this thesis; to assess the applicability and reliability of a vegetation index derived from an aerial imagery as proxy for crop health on complex smallholder farms. The use of such high-resolution aerial imagery could contribute to the modernization of SSA agriculture through the utilization of precision agriculture tools. This application of such a tool enables the delineation of sections of fields with different levels of crop vigour and thus allows for within-field crop health analysis even in such complex farming systems. This is important given that spatial variability in crop vigour has important implications for crop yield levels (Masino, Rugeroni, Borrás, & Rotundo, 2018).

There are, however, uncertainties regarding actual productivity levels as measured on smallholder farms (WorldBank, 2010). This uncertainty emanates, chiefly, from the complex nature of smallholder farms in SSA

(FAO, 2017b). The application of well-established approaches to crop yield measurement on complex smallholder farms in SSA is fraught with some significant deficits (Fermont & Benson, 2011; Sapkota, Jat, Jat, Kapoor, & Stirling, 2016). The *second objective* of the present thesis, among others, seeks to demonstrate the shortfalls of current yield measurement approaches in capturing agricultural productivity, especially when applied in the context of smallholder rainfed farming systems in SSA. A major hindrance to accurate measurement of smallholder productivity is the spatial character of the field itself. The loss of substantial proportions of farmers' fields in the course of the farming season implies that reliance on self-reports or even area measurement using the more objective Global Positioning System (GPS) devices is necessary but not enough. Here, the concept of *effective area*, rather than field area or planted area becomes fundamental.

Equally important is the need to understand the factors that drive current yield levels in SSA. Most studies seeking to unravel the yield conundrum confronting SSA farmers often undertake this endeavour through a conventional, top-down strategy. My approach in this study is a two-pronged one; analyse the sources of the poor crop vigour through the conventional, top-down approach as well as a bottom-up one in which smallholders' perspectives come into focus. Having observed substantial within-field variability in crop vigour and how this contributes to shortfalls in yield measurement, my *third objective* is to examine the factors contributing to within field variability in crop vigour. Several studies (Falconnier, Descheemaeker, Mourik, & Giller, 2016; Kassie et al., 2014; Niang et al., 2017; Srivastava, Mbo, Gaiser, & Ewert, 2017) have found a multiplicity of factors contributing to current yield levels. These studies do not, however, have the benefit of the holistic perspective that the use of UAV imagery offers. Analysing the source of crop yield variability at the farm scale from this vantage view helps shed more light on the sources of the poor crop yields in SSA agriculture. Biophysical and management factors are more often studied compared to socioeconomic factors in the quest to understand the yield problem in SSA. When analysed, however, socioeconomic factors have been found to be more explaining of yield levels (Mueller & Binder, 2015; Snyder, Miththapala, Sommer, & Braslow, 2016). My third objective thus also delves deeper to disentangle the underlying roles that socioeconomic factors play in the observed poor patches on smallholder maize fields.

The *fourth objective* relates to farmers' perceptions and attitudes to the presence of poor patches on their fields. This is important because how people understand a problem largely determines how they deal with it. Understanding smallholders' perceptions and attitudes is important given that what they think largely informs their decisions and farm management activities. Given the dominance of poor patches on smallholder fields, a reduction in their quantity, severity, and frequency has the potential to substantially improve crop yield levels. Smallholders' perceptions have, for example, been found to differ based on the degree of involvement with markets and their economic situations (Yaro, 2013), their supernatural beliefs (Callo-Concha, 2018) as well as their level of education and the extent of interaction with extension agents (Nigussie et al., 2017). Thus, analysing smallholders' knowledge sources and perceptions about crop yield-limiting factors is key to understanding on-farm investment behaviour and farm management (Moyo et al., 2012; Nigussie et al., 2017), which are both critical to improving productivity on smallholder farms in SSA.

1.2 Structure of the dissertation

The dissertation comprises a kappa and four research articles. The kappa consists of five chapters: the introduction, literature review, theoretical underpinnings, methodology, and discussions and conclusions sections. The introductory *Chapter One* consists of a general introduction of the study, description of the structure of the dissertation – this section, background of the study, the broad research aim and specific research questions that guided me, justification for the study, and a summary of the four papers that make up the dissertation,. *Chapter Two* reviews relevant literature for the study. I start by reviewing literature on measuring farm productivity and zoom in on yield as a measure of farm productivity. I then review literature on methods – both subjective and objective – for estimating yields as well as shortfalls of current measurement approaches with reference to the context of SSA. I also review literature on remote sensing of crops, showing the incremental progress made in this area of scholarship as well as the limitations of traditional remote sensing platforms relative to the SSA context as well as how UAVs can help fill this void. I then review literature on yield variability in SSA with specific focus on the sources of the variability and the fundamental but often overlooked role of socioeconomic factors in smallholders' yield levels. I end with some concluding remarks for the literature review chapter.

Chapter Three covers the theoretical underpinnings of the study. I draw on two grand theories: the Boserupian theory on agricultural intensification and the Chayanovian theory of the peasant economy. I also draw on the more practical, mid-range induced innovation model and the sustainable livelihoods framework (SLF). While the SLF is, strictly speaking, not a theory, it serves the useful purpose of being closer to the social reality that obtains among smallholder farmers in SSA and thus grounds the analyses. *Chapter Four* deals with the methodology employed for the study. I start with an introduction and then a synopsis of agriculture in Ghana as a whole, before narrowing down to the districts in which I undertook the study. I then describe the research design I adopted; a mixed sequential explanatory research design with the qualitative part of the study being preceded by the quantitative leg. The quantitative leg of the study involved plot and household sampling, household, and in-field surveys, as well as UAV flights over fields to collect remote sensing data. The qualitative part entails field observation and photo-elicitation interviews during which I conducted co-interpretation of UAV imagery of fields with smallholders. I then address concerns regarding ethics and positionality as well as validity and reliability of methods and conclusions. The chapter concludes with discussions on limitations of the study. *Chapter Five*, which is the concluding chapter, provides a synthesis of key findings of the study. The chapter then discusses the results of the study and relates these to the underpinning theories. It also addresses the specific contributions of this thesis as well as recommendations for future.

1.3 Background of the study

The overall aim is to improve food supply to countries in SSA as they face a major challenge producing enough food to feed their burgeoning populations. It is the only continent that continues to see an upward trend in the number of stunted children (FAO, IFAD, UNICEF, WFP, & WHO, 2018). Extant literature draw strong linkages between household food insecurity and stunting among children especially in low- and middle-income countries (Maitra, 2018). Much of SSA, thus still contends with food insecurity in many areas despite the significant improvements in nutrition and food security across the globe, particularly in the last half-century. For instance, despite the general progress towards the reduction of the prevalence of hunger, relative to the 1996 World Food Summit target of halving the number of undernourished people by 2015, SSA is the only region that has retrogressed in terms of absolute figures. Since 1990-1992, approximately 42 million more people have been added to the number of undernourished in SSA with the most recent estimates pegged at 217.8 million undernourished people (FAO, 2015a). More recent estimates of the direr nature of the food insecurity situation on the continent indicates that about 23% of the population may have endured chronic food deprivation in 2017 (FAO et al., 2018).

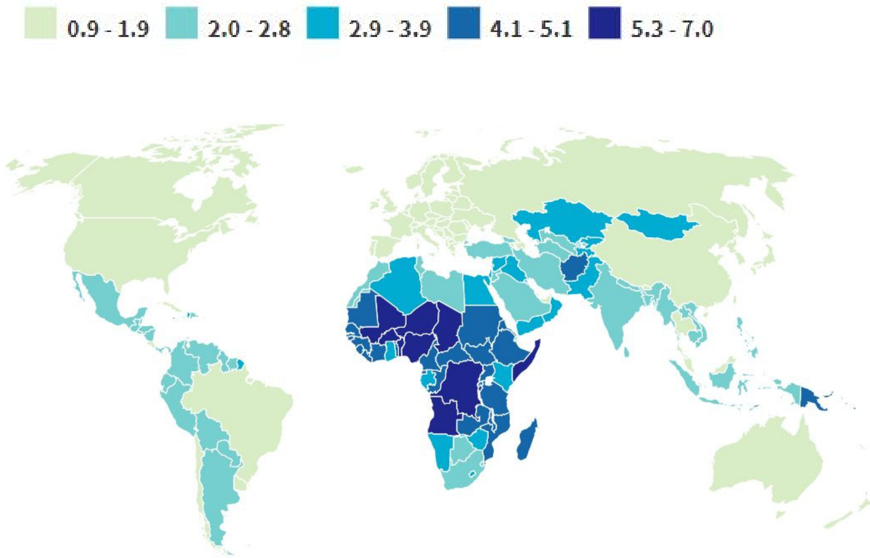

Figure 1. 1: Global total fertility rate map of 2019
Based on data from the UN Population Division. World Population Prospects: 2019 Revision.

These trends are not surprising given the rapid increases in population in SSA over the last half century. Figure 1.1 illustrates the most recent total fertility rates map of the world. As can be seen, the continent records the highest birth rates[1] globally. The average TFR ranges from 1.6 in Europe, 1.8 in North America, 2.1 in South America as well as Asia to a high of 5.0 in SSA (PRB, 2016)

Consequently, Africa's population has increased more than five-fold since the 1950s and currently stands at 1.3 billion (Canning, Sangeeta, & Abdo, 2015). Given the relatively young structure of the continent's population and the rapid declines in infant and child mortality, the rapid rate of growth of the population is expected to continue in the coming decades. This has important implications for the ability of the continent to feed itself.

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[1] Total fertility rate is the average number of children a woman is expected to have during her child-bearing years currently pegged at 15-49 years old.

To ameliorate this situation, there is an increasing dependence on food imports, particularly cereals, among SSA countries. For instance, while cereal imports constituted only 5% of local consumption in the 1960s when most of these countries gained political independence, this proportion increased to about 25% in the early 2000s (De Graaff, Kessler, & Nibbering, 2011). Indeed, AGRA (2017) estimates SSA's food import bill at between 30 and 50 billion dollars annually and expects this to more than double in the next decade if the situation does not significantly change. The increasing dependence on food imports is exacerbating the local food insecurity situation given the prevalence of chronic poverty which has effects on the purchasing power of the populace. As much as 40% of the population of the region live in landlocked countries and so in some regions of SSA, cost of transport constitute as much as 77% of the cost of food items (De Graaff et al., 2011). Thus, high transport costs significantly push food prices beyond the means of a significant percentage of the population[2]. The net effect is that most of the world's hungry people are smallholder producers and sellers of agricultural produce and their high number is not just a legacy from the past but the result of an ongoing process in the agricultural sector in developing countries leading to extreme impoverishment of scores of deprived smallholders (Mazoyer & Roudart, 2006).

In the face of these challenges, boosting local crop production seems to be the most logical route. However, compared with other regions of the world, SSA countries report some of the lowest yields per hectare (Affholder, Poeydebat, Corbeels, Scopel, & Tittonell, 2013; Chauvin, Mulangu, & Porto, 2012; Henderson et al., 2016). Using FAO data, Dzanku, Jirström, and Marstorp (2015) estimate that average cereal yields in SSA were about 57% of that of the world average in the 1960s. These production levels further reduced to 47% and 42% in the 1980s and 1990s, respectively, and have remained at around the 1990s levels to date. Over the same period, yields have been increasing in other developing regions such as Asia; so much so that by 2015, average cereal yields in that region were about 3% higher than the world average. This can partly be attributed to the failure of the Green Revolution technologies to improve crop production in Sub-Saharan Africa (Mazoyer & Roudart, 2006). Thus, whereas crop yields have grown significantly in other regions of the world, there is increasing evidence of stagnation and even yield

[2] There is a tendency to assume that high costs of food, especially the imported kind, should improve local agricultural production and thus benefit smallholder farmers in the long-run. While this may be true under certain conditions, the vast majority of subsistence farmers are net-buyers of food and often sell their produce when the prices are lowest (FAO, 2013; WorldBank, 2008).

collapse in SSA (De Graaff et al., 2011; Lobell, Cassman, & Field, 2009; Tittonell & Giller, 2013). Using panel data, Jirström, Archila Bustos, and Loison (2018) demonstrate deteriorating maize yields in a number of African countries. With Ghana, for example, the authors found that between 2002 and 2015, average maize yields reduced from 1.09 to 0.84 tonnes per hectare. The same was true for even the best performing 20% and 5% farms on which yields were reported to have reduced from 2.54 – 1.84 – 1.71 and 4.14 – 2.72 – 2.42 tonnes per hectare, respectively. Similar trends were discernible for Kenya and Malawi as well. Illustrations of Africa's lag relative to the rest of the world in maize yields is evidenced in **Figure 1.2** below.

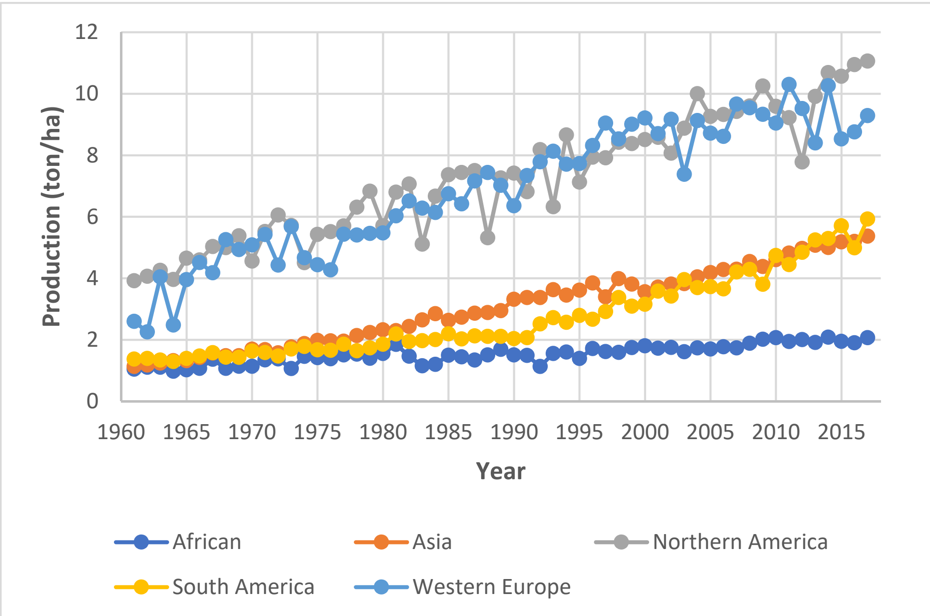

Figure 1. 2: Global comparisons of maize yield trends from 1960 to 2015
Based on FAOSTAT data accessed November 6, 2019

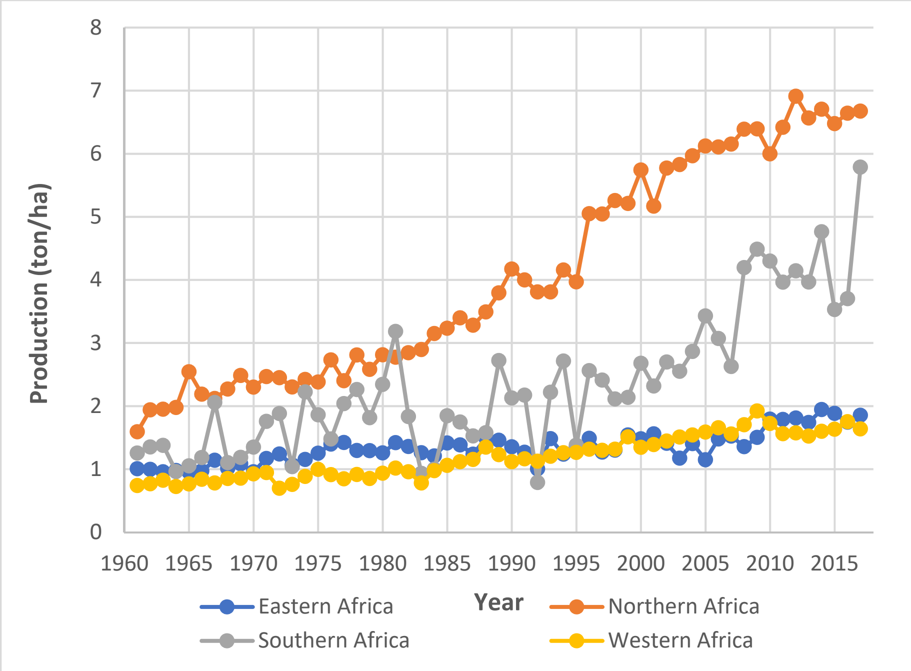

Figure 1. 3: African regional comparison of maize yield trends from 1960 to 2015
Based on FAOSTAT data accessed November 6, 2019

As **Figure 1.2** illustrates, global comparisons indicate that Africa is lagging behind the other production regions even though South America and Asia were at similar maize yield levels as Africa in the 1960s. By 2017, maize yields in Africa were well below 2.7 tonnes per hectare while those in South America and Asia had surpassed twice this level. Even within continental Africa, there are substantial regional differences. As shown in **Figure 1.3,** while maize yields were at similar levels in the 1960s in all four regions, the regional blocs of Northern and Southern Africa have seen relatively more significant leaps in maize yield levels; the latter showing a more erratic trajectory. In contrast, Eastern and Western Africa have seen maize yields lag with the latter performing the poorest. Thus, while maize yields have increased to 5.8 and 6.8 tonnes per hectare in Southern and Northern Africa, respectively, they are languishing at around 1.8 tonnes per hectare in Western and Eastern Africa regions. This is particularly worrying given the importance of maize as a staple crop both in Africa as well as at the global level[3] (Mourice, Tumbo, Nyambilila, & Rweyemamu, 2015; Shiferaw, Prasanna, Hellin, & Bänziger, 2011).

Narrowing down from the regional to the national levels, an interesting dynamic that emerges from an analysis of maize production and productivity is the large gap between attainable yields and actual yields farmers can obtain from their farms. Plant breeders from the West African Centre for Crop Improvement (WACCI) have produced maize varieties that yield up to 10 tonnes per hectare (Danquah, 2017). Even within the environmental constraints in which farmers operate, the Statistics, Research and Information Directorate of Ghana's Ministry of Food and Agriculture estimates attainable yields to be around 6 tonnes per hectare (SRID-MoFA, 2013). This notwithstanding, actual yields that farmers obtain from their farms is a meagre 1.8 tonnes per hectare (MaED-MoFA, 2014). Thus, less than a third of attainable yields are obtained from farms. Bringing actual yields closer to attainable yields is an important route to dealing with hunger and food insecurity in SSA.

Interestingly, however, while most of the global population growth will occur in Sub-Saharan Africa (PRB, 2012), this is concurrently the region most acutely confronted with some of the poorest agricultural yield levels (Affholder et al., 2013; Henderson et al., 2016). This is a conundrum and contradicts the Boserupian thesis, which essentially postulates that as population continues to increase, pressure is brought to bear on the existing agricultural system such that innovation would be stimulated and significant changes in agricultural technologies would be engineered to lead ultimately to increased agricultural productivity (Boserup, 1965). This of course is most applicable under pre-modern conditions when food production was largely local. Given how globalized the world has become, it is tempting to argue that not every part of the world needs to produce what it needs to consume.

The mainstream view prior to the global food crises of 2008 and 2011 had been that the Malthusian specter had been eliminated and that food insecurity was a symptom of distribution and access challenges, and not of production shortfalls (Gregory & George, 2011). The aftermath of these crises has however demonstrated our collective vulnerability to food shortages at both

[3] Across much of SSA, maize is one of the most important staple foods and forms a major part of the caloric intake of many African households in the form of Ugali in Eastern Africa, Sadza or Pap in Southern Africa and Banku and Kenkey in Western Africa, among others. In the global North, however, the importance of maize is seen mainly as cattle feed and as raw material for ethanol production.

micro and macro levels[4] (Wahab, 2014). Even at current significantly improved levels, Alexandratos and Bruinsma (2012) estimate that global food crop production should increase by at least 60% by 2050 in order to be able to feed a global population of more than 9 billion people while the FAO (2009) estimate that developing countries would have to almost double current production levels in order to meet the expected increase in demand. The pertinent question then is how this increase can be achieved. A number of studies such as Grassini, Eskridge, and Cassman (2013), Gregory and George (2011), and A. J. Hall and Richards (2013) have shown that the production of major food crops has reached a ceiling in most developed countries and are plateauing, while in developing regions, production is lagging behind. Thus, much of the needed increase in crop production would have to originate from developing regions, where most of the population growth is expected from anyway.

To meet this expected demand, two main pathways are usually available: intensification or extensification. Intensification generally entails increasing agricultural production from the same cropped area (van Ittersum & Giller, 2014) while extensification involves achieving the increases in crop production by expanding the currently cropped area. On the first pathway, uptake of new breeders has been shown to be largely limited in SSA with initial adopters often showing high abandonment rates (Keil, Zeller, & Franzel, 2005). Similarly, fertilizer use per capita has been poor in SSA for several decades now (Liu, Pan, & Li, 2015). With regards to the second pathway, while a substantial proportion of the modest gains in agricultural production in SSA are often attributed to extensification, this option is largely unsustainable in the long run. This is because the burgeoning populations, *vis-à-vis* the existing land tenure systems in most SSA countries, is contributing significantly to the phenomenon of shrinking farm sizes (G. Djurfeldt, Andersson, Holmén, & Jirström, 2011; Harris & Orr, 2014). Besides, Frelat et al. (2016) argue that bringing more land under cultivation does not automatically lead to increased production, pointing out that across SSA, land productivity systematically declines with increases in cropland holdings. Given concerns about losses of hitherto forested lands and biodiversity, increasing yields from farms currently cropped by smallholder, who constitute the vast majority of food producers, appears to be the most sustainable and logical pathway. This, however,

[4] The hoarding approach adopted by most of the major producers of the main cereals underscores the importance of self-sufficiency in own production. This, of course, brings into focus the broader question of the type of food system that we want to have. This is, however, beyond the scope of the present study.

requires an accurate and reliable measurement of current productivity levels on smallholder farms in SSA. A comprehensive and closer to reality estimation of smallholders' productivity levels is *sine qua non* to addressing the often-reported poor yields in this production context.

To recap, first, the great majority of SSA farms are small like those in the present study area, covering areas less than one hectare in size. Despite their small sizes, these small family farms constitute a large share of farm populations and produce most of the consumed food in SSA (FAO, 2014). Second, these small farms have historically produced food for a large share of the SSA population and are currently expected to continue to perform this role even in the face of growing demand emanating from the growing population. Third, a substantial proportion of smallholders are poor and unable to adequately feed their own families. Not only can increasing their yield levels improve their livelihood conditions by improving their access to food, it can also potentially improve crop sales and thereby increase their disposable incomes (FAO, 2012). This can then allow such smallholders and their households to invest and diversify. The present dissertation is concerned with farm productivity and yields because history has shown that yield development has almost always been a common basis for economic development and social progress. This motivation is aptly captured by Timmer (2005, p. 3) who posits that *"no country has been able to sustain a rapid transition out of poverty without raising productivity in its agricultural sector"*.

1.4 Research aim and questions

To contribute to this endeavour of improving crop yields, my research aim in this thesis is to augment our present understanding of crop productivity levels on smallholder family farms in a resource-poor context. To this end, I aim to (i) show the limitations of current methods of yield measurement, (ii) understand the factors contributing to current yield levels and variability; and (iii) analyse farmers' perspectives on their current productivity levels. To do this, I am guided by the following four research questions:

1. How accurate can a vegetation index derived from aerial imageries of smallholder plots be for estimating crop health and yields compared to in-field measures on complex smallholder farms?

2. To what extent do yield estimates based on farmers' self-reports differ from those based on crop cuts in the same plots? How much of this disparity is attributable to in-season plot area loss?
3. What is the relative contribution of various categories of factors to the observed yield levels? To what extent do socioeconomic factors underlie the observed yield variability?
4. How do smallholders in such resource-poor contexts perceive and deal with poor crop patches on their plots?

1.5 Research rationale

So far, agriculture[5] remains the only means to produce food for human sustenance. To this extent, ensuring that it can fulfill this mandate is crucial to our collective survival as humanity. Currently in SSA, there exists the paradox of a rapidly growing population co-existing with stagnating and even collapsing crop yields. Ghana's Ministry of Agriculture estimates that about 90% of farm holdings are less than two hectares in size with cultivation predominantly traditional; relying on the cutlass and hoe as the main farming tools (MoFA-SRID, 2010). Historically, a disproportionally high number of households are engaged in agriculture though this percentage has been on a steady decline and recent estimates put it at 46% (MoFA-SRID, 2017). The actual yields of maize, the most widely cultivated food crop by this population, is less than 2 t/ha though 6 t/ha is attainable on farmers' plots (Jirström et al., 2018; MoFA-SRID, 2017). The need to improve the tools of cultivation as well as the level of productivity on such smallholder family farms has not been in doubt.
It is, however, important that I point out the prevailing uncertainty in productivity levels. Shortfalls in the quality of statistics, especially those generated by national statistical services is well-documented in the literature (Jerven, 2013). While such shortfalls are neither new nor confined to SSA, their importance is underscored by the prominent role of the agriculture sector in the economies of African countries in terms of food security and poverty reduction (WorldBank, 2008). There are growing calls to revise the methods of yield estimation (FAO, 2017b). This clarion call is apt given that the last time such revision was undertaken is as far back as the 1980s (Carletto, Jolliffe,

[5] Defined broadly as the cultivation of crops and rearing of animals for consumption and other services. It, therefore, covers farming, forestry, fishing including aquaculture and hunting.

& Banerjee, 2015; Reynolds, Anderson, Slakie, & Gugerty, 2015) and the significant technological advancements that have occurred since then. While conventional methods of self-reports of crop area and output by farmers have been criticised as arbitrary, subjective and unreliable (Carletto, Gourlay, Murray, & Zezza, 2016; Gourlay, Carletto, & Winters, 2015; Sapkota et al., 2016), those touted as more objective – GPS area measurement and the crop cuts approach – are not without their own inherent shortfalls (Fermont & Benson, 2011). Remote sensing methods and approaches have often been touted as a keystone for improving agricultural statistics given recent advances on this front (Craig & Atkinson, 2013; Zhao, Shi, & Wei, 2007). However, their application, particularly in the context of SSA, has hitherto been largely limited due to some shortfalls associated with conventional remote sensing platforms of satellites and manned aircrafts on the one hand and in-field methods of ascertaining crop status, on the other hand. Significant technological advancements, especially in the last two decades, have occasioned the increasing application of UAVs as remote sensing platforms for agricultural research. Application of such useful, albeit experimental, tools has the potential to not only improve the quality and reliability of agriculture data in the context of complex smallholder farms but also serve as a source of farm intelligence to assist farmers in the management of their plots. My use of the UAV thus helps fill the spatial gap that hitherto existed and precluded SSA agriculture from the benefits of precision agriculture tools given the predominance of smallholder farms. This could contribute to improving productivity and yields in such farming systems.[6]

The poor productivity on maize farms in SSA is well-documented. The large gap between attainable and actual yields (Dijk, Meijerink, Rau, & Shutes, 2012; Kassie et al., 2014) as well as the significant spatial and temporal variability of yields (Bölenius, Stenberg, & Arvidsson, 2017) is equally well-documented. For such an important staple crop as maize, the existence of these gaps and variabilities have important implications for the ability of individuals and households to feed themselves (Masino et al., 2018), and ultimately achieve national food self-sufficiency. I argue that an appropriate starting point for dealing with such vexed issues in SSA agriculture is by getting a clearer understanding of the production and productivity levels of the most important producers. This leads to a better understanding of both immediate and

[6] In the short term, the target is not for smallholders who were the subjects of this study to individually adopt and own an UAV system. Not only is this not economical, it is also impractical. In the long term, however, whole villages could own an UAV system either through a cooperative or state agriculture support programme.

underlying factors that impinge crop productivity in the region. While climate-related factors are often assigned to explain spatial and inter-annual yield variations (Górski & Górska, 2003; Ray, Gerber, MacDonald, & West, 2015), the existence of significant variabilities even in the same agroecological regions and villages suggests other important factors are at play (Burke & Lobell, 2017; Farmaha et al., 2016; Gregory & George, 2011; Mourice et al., 2015). A more holistic understanding of the factors impinging yield levels and their variability at the village scale is thus crucial to improving overall production. Indeed, an across the board increases in the yield levels of each plot to the next quartile could substantially improve general yield levels not only at the village but also at regional and national levels.

In a nutshell, the overall aim is to improve food supply to a continuously growing population of SSA. The most prudent and sustainable route is to increase yields obtained from currently cropped farms. This is important because reliance on food importation have been shown to put food prices beyond the means of most poor households (AGRA, 2017; De Graaff et al., 2011), while extensification is environmentally unsustainable in the long run as arable land is a finite resource (Godfray et al., 2010). Smallholder family farms are critical because they already constitute the majority of producers and so increasing their production not only improves their food security but also potentially increases general farm incomes.

This dissertation focuses on maize because it is the single most important staple food crop in Ghana. With regards to general crop production, cocoa and maize are the two most important crops in terms of area of cultivation, production volumes, and value in sales. Maize is, however, more important than cocoa due to the more 'democratized' nature of its cultivation; according to the Sixth Ghana Living Standards Survey (GLSS-6, 2014) while about 800,000 households engage in cocoa cultivation, as many as 2.1 million households engage in maize cultivation. It accounts for more than 50% of total cereal production and is cultivated in all agro-ecological zones of the country (Akramov & Malek, 2012). Yields of maize per hectare are, however, low; only a third of achievable yields are currently attained on farmers' plots (SRID-MoFA, 2013). It is also important to point to the high level of consumption of own produce, particularly in rural areas. It is thus arguably the most important food security crop with a per capita consumption of 45 kg/person/year in 2010 (SRID-MoFA, 2013). Maize is the source crop for many Ghanaian foods including Abodoo, A-keegbemi, Akple, Apapransa, Banku, Etew, Kafa, Kenkey, Koko, and Obrayo, among many other foods and beverages. Thus, despite the low productivity attained on farmers' fields, it is an ideal crop whose increased productivity has the potential to reducing poverty and hunger (Wongnaa & Awunyo-Vitor, 2018).

Herein lays my rationale for undertaking this study. Improving production on smallholder farms is the aim but the starting point for that is to measure current productivity levels adequately and reliably. Thus, rather than to assume that yield measures that perform well in more advanced and homogeneous farming systems would suffice in the complex and heterogeneous smallholder farming systems of SSA, there is need to integrate modern techniques and tools to capture farm productivity in a nuanced way and by so doing also help improve yields.

1.6 Overview of the articles

This dissertation contains four journal-standard articles. **Article 1** (published in *Drones*) deals with RQ 1, which relates to the accuracy and reliability of a vegetation index derived from an UAV imagery for estimating crop health and yields compared to in-field measures on complex smallholder farms. **Article 2** (published in *GeoJournal*) deals with RQ 2 and examines the limitations of current measures of farm productivity as they relate to smallholder farming systems characterized by significant plot area loss during the farming season. In article 2, I demonstrate the significant disparity between yield estimates based on farmers' self-reported outputs and those based on the crop cuts approach and show how plot area loss contributes to this disparity. In **Article 3** (published in *Agriculture*), we analyse the sources of the within-plot variability in crop vigour and then discuss the specific role socioeconomic factors such as land tenure play in this variability. We also analyse the role that the security inherent in the tenure system in operation plays in decision-making regarding on-farm investments and the implications of these on yields. In **Article 4** (submitted to a peer-reviewed journal), we examine smallholders' attitudes to the prevalence of poor crop patches on their plots in the context of resource-poor communities in SSA. We find that, by and large, smallholders aim for optimization, rather than maximization, of yields. We also find that this attitude is based on rational thinking based on years of observation, knowledge, and experience. Each article thus relates to one research question in section 1.4 above, respectively.

2 Literature Review

> "Farms in the tropics, like farms everywhere, are adjusted to the circumstances of the environment in which farmers find themselves. This is particularly true of smallholder agriculture, which predominates in most tropical areas"
> - John D. MacArthur, in Hans Ruthenberg, 1971, p. 8.

2.1 Introduction

Given the common view that smallholder farmers, especially those in SSA, are some of the economically poorest (FAO, 2017a) and attain the least level of productivity on their farms (Affholder et al., 2013), meeting global targets on food security, poverty reduction and ultimately eradication, would require real improvements in their productivity levels. This is particularly true given that, despite the structural changes that have been ongoing for a couple of decades now (Alobo Loison, 2015; Andersson Djurfeldt, Djurfeldt, Hall, & Archila Bustos, 2018), most smallholders in rural spaces still spend a substantial proportion of their daytime and labour on their farms (Jirström et al., 2018). This notwithstanding, a large proportion of them are still net buyers of food (FAO, 2013). This implies that they do not produce adequate quantities of food to subsist on for the whole calendar year. Thus, the concept of subsistence farming; if defined as the kind of farming in which farmers grow food crops mainly to feed themselves and their families with little or no surplus, does not apply to most smallholders in SSA. Reversing this situation would require significant improvements in the yields of their staples or a total move away from agriculture. While the modernization theories suggest that, over time, deagrarianization or at least a move away from the subsistence kind of farming is inexorable, at any given time, the productivity of any population engaged in agriculture ought to reach a certain minimum threshold in order to be sustainable. There is, however, a contrary school of thought that argues that smallholder farmers are not as unproductive as they are often made out to be. Hence the need to take a second look at how productivity is measured in the contexts of smallholder farms in marginal agricultural regions. Be that as it may, though, there is also the need to revisit the tools and technologies that scores of farmers in less-advanced agricultures were not in a position to utilize when they were introduced as well as newer ones which all have the potential to boost agricultural yields and farmers' productivity.

To this end, in this chapter, I review the literature on yields as a productivity measure and its variability in marginal agricultural regions. Here, I discuss the main approaches to yield estimation as well as their shortfalls. By way of unutilized tools, I also discuss remote sensing of crops and the limitations that encumber its application in SSA. The application and applicability of UAVs, a more recent technology touted as having the ability to help farmers manage their farms more efficiently by filling the void of hitherto existing technologies is also discussed. Here, the discussion focuses on relevant areas such as plot size measurement and yield estimation. Under the same section, I also review the literature on yield levels and their spatial variability as well as the explanations often proffered for these. Also, within this section, I review literature on the underlying role that socioeconomic factors – relatively less considered in explaining yield levels – play in yield levels and their variability.

2.2 Yield as a measure of farm productivity

Like many other concepts, farm productivity cannot boast of a universally accepted definition; several have been put forth by different authors, mostly depending on their field of specialization or the perspective from which they approach the concept. From the agricultural geography perspective, farm productivity may be defined as output per unit of input or output per unit of land area so that improvements in farm productivity is considered to be the outcome of more efficient use of the various factors of production (Dharmasiri, 2012). Thus, actual yields farmers ultimately attain on their farms reflects their choices based on their own objectives, and perceived values and costs (Beddow, Hurley, Pardey, & Alston, 2015). Farmers' yield levels are important given the inextricable link between farm productivity and food security of smallholder farmers in most developing regions (Sapkota et al., 2016). Estimating farm productivity is, however, not a straightforward endeavour and requires accurate measurement of both inputs and outputs. With regards to inputs for example, factors of production such as land (area, and observable and unobservable quality), labour (quantity, skill, effort, task, and timing), capital (type and vintage) as well as inputs such as fertilizers, improved seeds and herbicides (both quantity and quality) are fundamental (Gollin, 2019).

Added to this complexity is the intermediating role that the technology used in the production process plays and this needs to be clearly understood and accounted for in the estimation of farm productivity (Beddow et al., 2015).

The apparently simplistic definition of output per unit of input turns out not to comprehensively cover all the important elements of farm productivity measurement. Even more limited is the definition of farm productivity as the output per unit of land, given that land is but one of several factors of production. It is in a similar vein that we could have other definitions of farm productivity to include output per unit labour, output per unit capital, and output for unit fertilizer, among others. Thus, all these are but partial measures of farm productivity (Beddow et al., 2015). A more complete and richer measure of productivity, which takes into account all the aforementioned factors of production instead of just one of them is the total factor productivity (TFP)[7] (Fuglie, 2018; Gollin, 2019). The FTP looks at how output varies in relation to changes in multiple inputs. For instance, an increase in the quantity of fertilizer applied will generally lead to an increase in, say, maize output per unit of land and a similar increase from improved technologies. Conversely, a TFP increase is achieved where a farmer can produce the same output with fewer inputs and thus at lower costs. The attractiveness of this measure of productivity derives from its comprehensiveness in taking into consideration the multiplicity of factors of production. A major shortfall of the TFP, however, is its data-intensive nature: TFP requires highly accurate and detailed measures of all inputs and all outputs (Fuglie, 2018). In the context of SSA smallholder farming, meeting these data demands in terms of the level of accuracy and detail is near-impossible in real life situations. Thus, while TFP is a useful measure of productivity particularly for global comparisons, it is hard to measure and sensitive to assumptions about the manner of combination of inputs to achieve a certain level of production.

Thus, despite its limitations, yield as a measure of farm productivity, defined as the output of a crop per unit of land used to produce it, is most preferred (Beddow et al., 2015; Fermont & Benson, 2011). As stated before, this is one of many partial measures of farm productivity. This notwithstanding, it is one of the most used measures of farm productivity due to its ease of calculation, intuitiveness, wide availability of time-series data on crop production and harvested area and, thus, comparability across locations (Gollin, 2019;

[7] Takes a systems approach and is defined as aggregate quantity of all outputs divided by the aggregate quantity of all the inputs used to produce those outputs (Alston, Babcock, & Pardey, 2010; Fuglie, 2018). Alston et al. (2010), however, admit that TFP is basically a theoretical concept and that all real-world measures omit some of the relevant inputs and outputs.

Reynolds et al., 2015). Its calculation requires the measurement of crop area and crop output as input variables (WorldBank, 2010). Yield, as a concept for measuring farm productivity, forms the basis of one of the longest standing debates in the agricultural development literature regarding the inverse relationship between the proponents of the farm size and productivity hypothesis (Dzanku et al., 2015; Todaro, 1985) as well as its doubters (Carletto, Savastano, & Zezza, 2013; Desiere & Jolliffe, 2018; Pol, 1984). Despite the longstanding nature of this debate and the academic attention it has attracted, it is nowhere near settled.

The difficulties associated with using yield as the measure for farm productivity is further compounded in the context of SSA farming systems, which are dominated by smallholder farms characterized by the simultaneous cultivation of multiple crops on the same plot (Fermont & Benson, 2011; Reynolds et al., 2015; Yengoh, 2012). Given the ubiquity of intercropping in such farming systems, the pertinent question then is how one treats secondary crops, which may be annual – cassava – or triannual ones – groundnut – in the context of maize farming. This is germane given that these intercrops would compete for the same nutrients in the course of the farming season. Besides, the measurement of land used in the production, which is the other variable for estimating this measure of farm production, often only relies on the plot area (Fermont & Benson, 2011; WorldBank, 2010) while not accounting for both observable and unobservable quality of the land (Gollin, 2019). Even taking only area into consideration, the specific area to be used: whether planted area or harvested area ought to be clarified. This is relevant given the tendency for smallholder farmers to experience crop area loss in the course of the season (Reynolds et al., 2015). Based on this, it becomes even more important that studies, which rely on self- reports of plot area, specify which area – planted or harvested – that farmers are reporting.

Thus, while there are more comprehensive measures of farm productivity such as the TFP, the commonest and most applied measure of farm productivity is that of crop yields. The popularity of the latter is due largely to its simplicity and ease of calculation, as well as comparability across multiple locations.

2.3 Methods of crop yield estimation

Following from the above, there has been a resurgence of debates in the last decade on the adequacy of current measures of yield as farm productivity measure. This resurgence is due, at least in part, to the World Bank's identification of improvements in the measurement of farm productivity as a priority area of research (WorldBank, 2010). The need for this intervention is well overdue given that the previous comprehensive guide to yield estimation was in the 1980s (Carletto et al., 2015; Reynolds et al., 2015). Against the backdrop of significant technological advances – both in hardware and software – since the 1980s, such a revision is most pertinent. While challenges with regards to agricultural statistics are global in scope, and thus not limited to SSA, it is a much more dire challenge in the sub-region given the predominance of smallholder farms, their linkages to households food security and importance in national economies, as well as the predominance of intercropping (Carletto et al., 2015; Fermont & Benson, 2011; Reynolds et al., 2015).

2.3.1 Subjective farmer self-reports

The main source of global data on agricultural productivity assessment is the FAO though it is fraught with some well-known deficiencies (Fuglie, 2018). Given these shortfalls, Alston et al. (2010) caution again placing too much premium on such global agricultural productivity measures, especially those relating to TFP. This notwithstanding, the most important source of agricultural production and productivity data is the corporate statistical database of the Food and Agriculture Organization (FAOSTAT). The statistics for this database are sourced from national statistical services of FAO-member countries. These statistical services, in turn, collect much of their data through surveys, administrative data and estimates based on expert observations. The commonest medium involves the collation of information collected through in-person interviews in household and farm surveys (Lobell et al., 2018). For example, the Ghana Census of Agriculture survey conducted by the Ghana Statistical Service and the Ministry of Food and Agriculture solicits farmer-reported information on plot area, crop output, and input use, among others at the plot scale.

Self-reports of plot area and crop outputs are, thus, the most widely used and are the main source of data for most agriculture databases. Their popularity is borne out of their convenience, cost-effectiveness, and efficiency as well as their applicability in diverse farming systems. Farmer estimations of crop outputs could either be from *predictions* – quantity of crops farmers expect to harvest at the end of the farming season from a given plot or *recall* – the quantity they did harvest (Fermont & Benson, 2011). For output predictions, visual estimations of crop vigour and yields are most accurate at maximum stages of crop growth (Singh, 2003), and ideally with the farmer and enumerator in visual contact with crops (Fermont & Benson, 2011). The reliability of such predictions, however, depends on the previous seasons' experiences of the farmer on each plot. Farmer recalls of crop output is, however, done sometime after harvest either at the residence of the farmer or the storage location of the output to enable validation.

While Fermont and Benson (2011) argue that farmer estimations of crop outputs have relatively high accuracy, Carletto et al. (2015) assert that such estimations are ridden with a high degree of arbitrariness and subjectivity; contributing to significant errors. Sources of these errors include the tendency to round off quantities; not accounting for in-kind payments to relatives, farm labourers, and landowners; poor recollection of historical outputs; poor quality of responses in prolonged interviews; the tendency to average outputs over several seasons; deliberate under- and over-reporting as well as errors arising from conversions from non-standard units (Fermont & Benson, 2011; Gourlay, Kilic, & Lobell, 2017; Sapkota et al., 2016). With regards to errors due to conversion from non-standard units, the maize crop is one of the most susceptible crops. Carletto et al. (2015) posit that significant portions of the total production of maize may be harvested while still green, and particularly in the context of food-insecure communities. They point out that this is a major source of error because not only do most surveys not collect data on such fresh maize harvest, even the ones that collect such information have difficulty converting such quantities in an accurate manner.

In the same vein, several studies have documented the substantial inaccuracies that result from reliance on farmers' self-report of their plot area (Carletto et al., 2015; Carletto et al., 2013; Desiere & Jolliffe, 2018). Sources of such inaccuracies include both unintentional misreporting arising from limited technical skills and relevant education, tendency to round off and variations in measuring units from one village to another, as well as deliberate misreporting for fear of taxation or a belief of standing to gain benefits depending on their reported farm sizes (De Groote & Traoré, 2005; Fermont & Benson, 2011). Interestingly, Fermont and Benson (2011) found that the reliability of farmer estimates of crop area varies between countries with SSA farmer estimates being most inaccurate. Even more interesting, the inaccuracy is further affected by crop type and plot size with a tendency to overestimate the area of smaller plots and underestimate larger ones (Carletto et al., 2013). De Groote and Traoré (2005), for instance, found that farmers overestimate plots less than one hectare, with farmers able to provide more accurate estimates of cash crop plot sizes than for those of food crops including cereals. In spite of these shortcomings, most countries still depend on farmer self-reports of both crop output and plot area to estimate yields and thus still form the basis of the primary databases for their agriculture data.

2.3.2 Objective measures using crop cuts and GPS

Given these shortfalls of farmer self-reports of both crop outputs and plot area, more objective methods for deriving these variables for estimating crop yields have often been recommended. For crop output, methods include crop modelling (both empirical and process-based), allometric models, purchasers' records, crop insurance data, crop cards kept by farmers, expert's assessment, sampling of harvest units, grain weighting, whole plot harvest, crop cutting, and remote sensing approaches (Fermont & Benson, 2011; Sapkota et al., 2016). Of these, whole plot harvest is said to be the most accurate method for measuring crop outputs. It is, however, more feasible on demonstration plots and less so on farmers' plots, especially in cases of large scale surveys (Sapkota et al., 2016) due to time and cost constraints. Additionally, crops with definite maturity dates such as cereals are easier to harvest in a whole plot harvest operation compared to those with indeterminate growth habits such as beans and cassava (Fermont & Benson, 2011). Similarly, staggered planting, another common practice among smallholders in SSA, tends to complicate whole plot harvesting by researchers. The above notwithstanding, whole plot harvesting is ideal for capturing most complete output for plots given that it includes post-harvest losses, which could be excluded in farmer-reported outputs. Thus, this method offers the least level of bias and error for deriving crop outputs from plots.

Considering the impracticality of the approach of harvesting whole plots for the purposes of quantifying crop outputs, crop cutting[8] is often considered the gold standard, especially for cereals but also, to a lesser extent, for roots and tubers (Carletto et al., 2015). Since its development in the 1950s in India and subsequent endorsement by the FAO in the 1980s, this method has gained widespread recognition as a more objective method for output and yield measurement. With this method, a subplot or a number of subplots are randomly demarcated using various means and crop outputs from these subplots are harvested by trained field staff, and this then forms the numerator of the yield formula (FAO, 2017b; Fermont & Benson, 2011). The number and

[8] Crop cut refers to a set of methods for estimating crop yield by harvesting a small portion of fields. While procedures differ, the goal generally is to scale up the yield from the sampled plots to estimate a yield for the entire field (Beddow et al., 2015). A fundamental assumption of the CC approach is the homogeneity of crop vigour within each field.

size of subplots generally range between 1 to 5 and 0.5 to 50 m^2, respectively, depending on available resources and level of precision desired (Sapkota et al., 2016).

Although it has been touted as being more objective, the crop cutting method has its own inherent shortfalls. These shortcomings could be substantial on relatively small, irregularly-shaped plots with uneven plant density (Fermont & Benson, 2011); an apt description for a large proportion of smallholder farms in SSA. Recommendations for dealing with plots with variable crop performance range from increasing the number and size of subplots to using a neutral person – not the researcher, the farmer nor the extension officer, and even blindfolding the person selecting the subplot (Sapkota et al., 2016). Even with such elaborate precautions to ensure randomization and, thus, improved reliability and objectivity, other shortfalls such as edge, border, and harvest effects, weighing errors as well as the costly and time-consuming nature implies that the crop cutting approach to output measurement is not frequently used by researchers. Despite these shortfalls, crop cutting as a method for deriving the crop output is said to be the best among the current methods available for the purpose.

Similarly, methods for deriving plot area include the collective estimation by farmers and enumerators, the polygon method of actual area assessment, the rectangulation and triangulation methods, P^2/A method, compass and rope, GPS area measurement, as well as remote sensing and GIS methods. All these methods come with various degrees of efficiencies and shortfalls. Considering these shortcomings, the GPS method of area measurement, just as is the case with crop cuts, is often regarded as the gold standard given that it drives more objective outcomes. A major advantage of the GPS method is that it is immune from the potential biases associated with the characteristics of respondents and the use of non-standard units of measurement (Carletto et al., 2016; Kilic, Zezza, Carletto, & Savastano, 2017). Thus, the GPS area measurement is regarded as best-among-the-rest and holds the potential to significantly improve the accuracy of agricultural data in the context of household surveys (Carletto et al., 2013).

2.3.3 Shortfalls in their application in SSA

While the crop cuts and the use of the GPS have been trumpeted as the most objective methods for measuring crop output and plot area, respectively, their applicability and suitability are also, largely, context-dependent. While traversing, otherwise known as the rope and compass method, has been shown to be the most accurate method of area estimation, it comes with a disadvantage of being overly burdensome and time-consuming and thus impractical in large household surveys (Carletto et al., 2016). It is for this shortcoming and against the backdrop of substantial advances in GPS technology that the latter has become the most-favoured method of area measurement in contemporary times given its relative efficiency in terms of time and labour requirements (FAO, 2017b). However, the use of the GPS also requires meticulous training of enumerators and can be costly given that it requires enumerators to visit and walk the perimeter of each plot (Gollin, 2019). Furthermore, the advantages of the GPS method of area measurement such as rapidity, time-efficiency, and ease of application are counterbalanced by its shortcomings relating to regions with significant cloud cover, large trees on plots and hills with plots on slopes (FAO, 2017b). While these shortcomings can be overlooked on larger plots, the errors resulting from GPS area measurement on small plots – less than 0.5 ha – could be substantial (Fermont & Benson, 2011). This shortfall is by no means trivial given the ubiquity of smallholder farms of area less than 0.5 hectares in SSA (SRID-MoFA, 2013). There is also the tendency for enumerators to cut off corners to save time or avoid walking in thickets and wet areas or even not surveying distant plots altogether (Carletto et al., 2016; Gollin, 2019). All these can contribute to potential sources of errors and biases in GPS plot area measurement. With regards to missing GPS area data, Kilic et al. (2017) posit that careful multiple imputations of values, augmented by farmer SR area can work effectively to overcome the possible biases.

It is crucial to point out that beyond the sheer size of a plot is the quality. Both the observable and unobservable quality of a plot have even more significance for its productivity. Observable soil quality characteristics include soil type, structure, texture, as well as land slope, drainage, and topography. Using panel data from Tanzania and Uganda, Gollin and Udry (2019) find that measurement error and plot heterogeneity collectively account for a substantial proportion of the dispersion in measured productivity. The authors argue that unobserved heterogeneity in soil quality is important in accounting for differences in productivity across farms. The implication of this is that, no matter how accurately land area has been measured, to the extent that the intrinsic properties of land vary, caution ought to be exercised in treating plot area as the only land input in productivity measurement (Gollin, 2019). Given the spatial variability in the quality of land, the question of whether to use planted area or harvested area becomes an important one (Alston et al., 2010). Plot heterogeneity not only has implications for plot area as a variable for the farm productivity measurement. The heterogeneity also has consequences for crop output measurement using the crop cuts approach.

Besides, other biases inherent in the CC approach to output estimation, as enumerated by Fermont and Benson (2011), include the edge, border, and harvest effects, non-random location of subplots as well as weighing problems. For instance, the edge effect, which is the inclusion of plants that actually fall outside of the CC subplot can be significant, especially for randomly planted plots and may thus give an upward bias, which could be as high as 30-40% in small plots (Fermont & Benson, 2011). While the number and size of the subplots have implications for the accuracy of the measure, resources availability can also be restrictive. An important source of weakness of this approach is not just the number of subplots but rather how the subplot is demarcated (Sapkota et al., 2016). Two important tendencies often conspire to upwardly bias crop cuts as an output measurement approach: the tendency for the border of plots to have poorer crop vigour and the inexorable inclination of enumerators to, either consciously or unconsciously, avoid poorly performing sections (Fermont & Benson, 2011). Sapkota et al. (2016) argue, therefore, that in a field with variable crop performance – and this is largely the case in most smallholder farms in SSA – it is advisable to use even larger sampling frames or increase the number of subplots per plot. Of course, similar to full plot harvest, this would have implications for cost and time in large surveys.

Other confounding factors of yield measurement in SSA agriculture include the multiple use of the same piece of land. In a developing country context where mixed farming systems predominate, land area under cultivation may simultaneously be used for several other activities; some of which may have non-agricultural components. This may further complicate the measurement of the plot area and using it as the basis to deduce the level of productivity (Gollin, 2019). Even with just agricultural production, but excluding animal rearing, measuring productivity in mixed cropping systems is not a straightforward endeavour. This is especially the case with more than two crops on the same piece of land simultaneously or multiple cropping cycles within the same season, otherwise called relay cropping (Fermont & Benson, 2011). The latter leads to a situation whereby it is virtually impossible to estimate crop area for constituent crops and yet failure to take into consideration the existence of multiple crops would result in gross underestimation of productivity (FAO, 2017b). It proposes ways to deal with this conundrum through apportionment of the area to the various component crops, either subjectively by eye estimation or by more objective means such as using plant density.

Another confounding factor, especially with regards to maize crops, relates to the harvest of the crop while still green – a common phenomenon, particularly in the context of relatively food-insecure households. Such harvests are usually not structured and take place over a couple of weeks. The recording of such early harvests can be fraught with errors – both measurement and conversion errors – given smallholder's proclivity to round off figures when reporting such harvests (Fermont & Benson, 2011). Surveys that rely on self-reports of outputs, therefore, must specifically probe for such harvesting. With regards to the crop cuts approach, farmers could be entreated not to harvest any green maize from subplots demarcated for crop cut harvests.

Additionally, loss of crop area in the course of the farming season is another source of complication arising from the use of plot area to estimate farm productivity. Loss of crop area could be the result of poor germination, damage from pests and diseases, animal grazing or extreme weather conditions such as droughts or floods; the latter leading to erosion activities, as well as crop theft, and abandonment due to unusual economic conditions (Craig & Atkinson, 2013; Fermont & Benson, 2011). While area loss is common in smallholder farms in SSA and further complicates yield measurement (Sapkota et al., 2016), many studies fail to specify whether they define crop area as planted area or harvested area and this could significantly impact yield levels (Alston et al., 2010). Using plot-level data from Tanzania's National Panel Survey, for instance, Reynolds et al. (2015) found that, although it may be infrequent on trial plots, area losses are substantial on smallholder plots; with as much as 23% of the sampled plots experiencing plot area losses. The authors posit that smallholder farmers are far more likely to experience area losses because they tend to intensively cultivate marginal plots without adequate replacement of soil nutrients. Given these shortfalls of existing approaches to measurement of farm productivity, recent efforts have been focused on exploring integration of remote sensing and geographic information systems to monitor crop vigour and yields and *Article 2* addresses this.

2.4 Remote sensing of crops

Remote sensing[9] (RS) of crops has been touted as having the potential to become a keystone for improving agricultural statistics in the near future (Zhao et al., 2007), although it is already widely used in some regions. The RS approach trumps in-field methods such as GPS area measurement and the crop cuts approach to crop output measurement with regards to its ability to

[9] Defined as the art, science and technology of obtaining information about an object, area or phenomenon through an analysis of data acquired by a device that is not in direct physical contact with the object under study (Lillesand, Kiefer & Chipman, 2015).

ascertain crop status due to its ability to capture a large swath of land instantaneously (Chapman et al., 2014; Jones & Vaughan, 2010). While remote sensing of crops is not a novelty, it has gained a resurgence in the literature in the last 2-3 decades. This has been bolstered by two main occurrences: the US Geological Survey's decisions to make the entire archive of Landsat data freely available and the massive improvements in computing power (Lobell, 2013). The former development precipitated the proliferation of other satellite resources while the latter development has enabled the production of much more powerful and cheaper sensors and computers for the acquisition and processing of satellite imagery at hitherto unprecedented rates. The combined result of these developments has been a substantial increase in the application of satellite data in agriculture for mapping crop area and weed-crop discrimination (Bisht et al., 2014; Jovanović, Govedarica, & Rašić, 2014; Roumenina et al., 2015); estimation of crop nitrogen requirements (Pinter et al., 2003; Yao et al., 2015); monitoring and assessing crop growth and vigour (Frazier, Wang, & Chen, 2014; Liang et al., 2016); and yield estimation and prediction (Imran, Stein, & Zurita-Milla, 2015; Jaafar & Ahmad, 2015; Lobell, 2013).

Despite these advancements in the field of remote sensing of crops, several limitations associated with satellite imagery, the primary and conventional remote sensing resource, have restricted its usage in the context of smallholder farms in SSA. These limitations include significant cloud covers impeding visibility; the complex and heterogeneous nature of the predominant farming systems; unavailability and even where they are available, poor quality of crop yield databases in the region; and the generally coarse spatial and temporal resolution of most readily-available satellite resources in the face of the small plot sizes (Cheng, Yang, Inoue, Zhu, & Cao, 2016; Jaafar & Ahmad, 2015; Son, Cheng, Chang, Duc, & Nguyen, 2013; Wójtowicz, Wójtowicz, & Piekarczyk, 2016). That is, while satellite remote sensing has been implemented in monitoring crops status, and predicting and estimating crop yields, with a large degree of success in advanced agricultural systems, replication of this in SSA has been largely dogged with these limitations. The recent availability – albeit on a commercial basis – of finer-resolution satellite sensors such as those on the SPOT 5, QuickBird, and the IKONOS satellite systems, has somewhat helped ameliorate the spatial resolution difficulties that confront satellite remote sensing of crops in such contexts.

In more recent times, a number of studies (Burke & Lobell, 2017; Lobell et al., 2018) have used paid-for, higher-resolution satellite data to achieve similar results in SSA as has previously been achieved in more advanced and homogeneous agricultural systems. Notwithstanding these recent advances, the application of such satellite imagery for estimating smallholder farm productivity has had mixed results. On the one hand, the results obtained by Burke and Lobell (2017) using the 1meter-resolution Terra Bella imagery in Western Kenya demonstrates the potential that this higher resolution imagery holds and proves productivity estimates roughly as accurate as those based on conventional, survey-based measures are attainable. On the other hand, Lobell et al. (2018) found that, even with the use of such high-resolution satellite data in Uganda, satellite-based yield estimates were less well-correlated with ground-based measures in intercropped plots compared to pure stand plots. This implies that there are more hurdles to overcome.

2.4.1 Vegetation indices, crop vigour and yields

The electromagnetic radiation, which travels in a vacuum in the form of waves of differing lengths, is the medium of information communication in remote sensing; with the most relevant wavelengths for crop sensing being the visible light, near-infrared, and shortwave infrared (Wójtowicz et al., 2016). Plant characteristics such as type, amount, and the condition can be spectrally depicted based on the amount of light they reflect in these bands through vegetation indices. Also, growth-associated characteristics of plants such as the production of chlorophyll can be quantified using remote sensing platforms to calculate vegetation indices (VI) based on reflectance of different spectra from the canopy of crops (Chapman et al., 2014). A VI may be defined as the ratio, difference, ratioing differences and sums, or by forming linear combinations of spectral band data and are usually derived from radiometric data (Jackson & Huete, 1991). They are primarily used to indicate the amount of green vegetation present and are based on the sharp increase in reflectance from vegetation that occurs around 700nm on the electromagnetic spectrum (Jones & Vaughan, 2010).

The most commonly used VI, the Normalized Difference Vegetation Index (NDVI), which quantitatively measures vegetation conditions, was first postulated by Rouse, Haas, Schell, and Deering (1973). It is, essentially, a ratio of the difference and sum of the reflectance in NIR and red regions. Thus, NDVI = (NIR-R) / (NIR+R), where NIR represents the pixel values in the near-infrared band and R represents the pixel values from the red band. The variances in reflectance properties of the infrared and red bands enable one to assess density and intensity of vegetation using the reflectivity of solar radiation. The utility of a VI such as the NDVI rests on its high correlation with biophysical parameters of plants and low sensitivity to others such that signals from vegetation are enhanced while minimizing solar irradiance and soil background effects (Jackson & Huete, 1991).

The statistical-empirical relationship between vegetation indices and crop yields is, thus, the basis of remote sensing of crops and yields (Wójtowicz et al., 2016). Jones and Vaughan (2010) explain that VIs such as NDVI generally estimate ground cover as an indicator of the leaf area index, which in turn can indicate differences in productivity and hence crop yields. They, however, point out a more direct and functional relationship between NDVI and crop leaf chlorophyll contents, and from the latter to canopy nitrogen and then to crop yields. Sinclair and Rufty (2012) concur with the latter relationship when they point out that strong relationship between increased nitrogen input and improved crop yields. Thus, the simplest and commonest approach to estimation of yield per unit area is the exploitation of these well-known relationships. Piekarczyk, Sulewska, and Szymańska (2011), for instance, found that the relationship between spectral indices and yields from oilseed crops was strongest (R^2=0.87) at early flowering stages; and that, while increasing presence of flowers weakened this relationship, especially in the visible range, this was largely reversed at full flowering in the NIR band. Similarly, Swain, Thompson, and Jayasuriya (2010) found that NDVI values at the panicle initiation stages of rice were highly correlated with total biomass and yields, with regression coefficients of R^2=0.76 and R^2=0.73, respectively.

2.4.2 Unmanned aerial vehicles filling the gap

In the wake of the limitations associated with satellite remote sensing of crops in SSA, other remote sensing platforms are having to be used to bridge the gap. Manned aircraft have, for instance, been used to circumvent some of the challenges that confront satellite remote sensing. This notwithstanding, manned aircraft also have their own set of disadvantages such is high costs, competition for operations, and the need to expend resources to fly from often far off airfields before reaching target plots (Matese et al., 2015). Significant advances in computing has led to improved electronic imaging and sensors, and has contributed significantly to major breakthroughs in digitalization, miniaturization, navigation equipment, design of light-weight materials and small aircraft and a concomitant ease of use and reductions in costs (Pozo, Rodríguez-Gonzálvez, Hernández-López, & Felipe-García, 2014; Zhang et al., 2016). These have substantially created avenues to dealing with hitherto nagging challenges to crop remote sensing. Following these significant breakthroughs, the use of Unmanned Aerial Vehicles (UAVs) as remote sensing platforms is fast gaining ground (Pozo et al., 2014).

The application of UAVs successfully bridges the gap between satellite and manned aircraft as remote sensing platforms on the one hand and the more laborious and time-consuming traditional field surveys on the other hand. Yang and Hoffmann (2015) have catalogued some of the advantages that UAVs, as remote sensing platforms, hold over satellite and manned aircraft including relative lower costs, easier deployment, near-real-time imagery availability for initial visual assessment, less competition for images, as well as limited weather-related challenges such as with cloud cover. UAVs also trump other platforms in the area of spatial and temporal resolution (Matese et al., 2015). Other advantages of the use of UAVs is that due to their lower flying altitudes, UAVs are able to use less expensive sensors compared to manned aircraft and satellites. Besides, the speed of deployment and data collection capability in inaccessible plots such as waterlogged area comes in handy and thus trump ground-based surveys where the object is to eliminate potential damage to the canopy of taller crops such as maize (Chapman et al., 2014). Thus, UAVs have been shown to outperform other remote sensing platforms in a variety of research settings. For instance, Sakamoto et al. (2013) found that camera-derived vegetation indices are closely related to those derived from SKYE and MODIS reflectance and the former are good proxies of crop biophysical characteristics. Similarly, Matese et al. (2015) compared NDVI derived from satellite, manned aircraft, and UAV and found that while the different platforms provide comparable results in characterizing spatial variability, in more heterogeneous vineyards, relatively coarser spatial resolution satellite imagery failed to adequately represent the intra-vineyard variability. They conclude that the UAV platform is advantageous for relatively smaller areas with high heterogeneity and that a break-even point exists at five hectares beyond which other platforms may be preferable.

Admittedly, most of the studies that have employed UAVs for remote sensing of crops have been undertaken on experimental plots rather than real farm plots or in more advanced farming systems. For instance, Laliberte, Goforth, Steele, and Rango (2011) achieved an overall accuracy of 87% on a species-level vegetation classification as well as obtained very good correlations between ground and airborne spectral reflectance (R^2=0.92). Similarly, Torres-Sánchez, Peña, de Castro, and López-Granados (2014) obtained accuracies of between 92% and 88% for a variety of indices depending on flight altitude. They then concluded that UAV flight parameters should depend on factors such as objectives of the study and the terrain to be surveyed. In addition to terrain, flight altitudes should be decided on the basis of the degree of detail to be achieved (Mesas-Carrascosa et al., 2015).

More recently, O. Hall et al. (2018) have bucked this trend and used a UAV system equipped with vertical take-off and land (VTOL) capabilities and mounted with two consumer-grade cameras; one which has been modified to capture images in the near-infrared on smallholder farm plots in the Eastern Region of Ghana. The authors demonstrated the suitability of such a set up for delineation and classification of maize - accuracy of above 94% - as well as calculate the vegetation fraction, an important parameter in yield estimation in a heterogeneous smallholder farming system. It is within this context that *Article 1* of the present thesis demonstrates, using the variant of the normalized difference vegetation index that relies on the green band rather than the red, that vegetation indices derived from UAV imagery more accurately, reliably and timeously predict not just crop vigour but also yields on smallholder plots, compared with in-field methods of visual scoring and SPAD meter readings. It shows that even in more complex farming systems in SSA, UAVs outperform in-field approaches with regards to ascertaining crop status in the course of the farming season in terms of timeliness, accuracy, and reliability.

2.5 Crop yield variability in smallholder farms

Yield levels and their variability are important to the extent that they contribute to a region's ability to meet its food and feed needs. This view is justified against the backdrop of the series of global commodities price hikes that occurred in the last decade despite large regional differences in production and productivity capacities. Crop yield variability may be analyzed temporally or spatially. Temporal – inter-annual – crop yield variability relates to variability over time while spatial or geographical – inter-farm – yield variability relates to yield variation over space. Both kind of variabilities are crucial to the food systems of nations (Ben-Ari & Makowski, 2014; Kassie et al., 2014; Ray et al., 2015) and this is particularly true for marginal production regions such as SSA, given that most smallholder farmers in this region are still net buyers of food. Much of the latter kind of variability is often attributed to differences in climate and other growing conditions. But for the current study, reference to yield variability connotes the spatial kind of variability. Yields have been shown to vary significantly, particularly in rainfed family farms in tropical regions (Affholder et al., 2013). Smallholder farming in this region is still characterized by significant crop yield variability and this variability is persistent even within the same agroecological zones and farm plots (Falconnier et al., 2016; Ronner et al., 2016).

Literature on yield variability may be categorized into two: the first category treats yields in absolute terms, while the second analyses yields levels in relation to a reference or potential yield. The potential yield could be simulated potential yields or the average of the top ten percent of the yields in a region or locality – frontier yields (Neumann, Verburg, Stehfest, & Müller, 2010). The latter could also either be based on yields obtained from research stations or farmers own plots in the localities where the study took place. However, data from trial plots generally do not represent real farms in terms of soil properties and crop management (Beza, Silva, Kooistra, & Reidsma, 2017). This second strand of literature often expresses yield variability as a percentage of the reference yield. Examples of the studies that treat yield variability in absolute terms include Falconnier et al. (2016), who find significant crop yield variability in southern Mali with maize yields ranging from 0.20 to 5.24 tons/ha on control plots. Similarly, Rurangwa, Vanlauwe, and Giller (2018) find that in Rwanda, maize yields ranged from 0.8 tons/ha in controls to 6.5 tons/ha in treatments previously fertilized with phosphate and planted after common bean; and from 1.9 tons/ha in controls to 5.3 tons/ha for maize grown after soybean. Mourice et al. (2015) find substantial actual maize yield variability in the Wami River sub-basin ranging between 0.05 tons/ha to 3.6 tons/ha with an average of 0.86 tons/ha. These figures show substantial within-country variability in maize yields even within similar cultivation contexts.

For the second category of literature, which analyses yield variability relative to a reference yield, Neumann et al. (2010) report actual maize yields to be 40% of their frontier yields in West Africa. Similarly, Tittonell and Giller (2013) find that average yields range from 40 to 60% of potential yields in more fertile plots and a meagre 10 to 20% in poorer plots; and Mourice et al. (2015) find actual maize yields to be a meagre 21% of simulated yields. Having found similar substantial yield variabilities across several sites in SSA, Henderson et al. (2016) conclude that there are no clear patterns and that the continuum of variability cuts across both East and West African sites. It is pertinent to point out two important caveats: first, the use of potential or theoretical yields as reference can often mask important yield differences within and across plots; and second, reliance on experimental stations' reference yields may be misleading as these are often located in the most productive environmental conditions and thus tend to overestimate attainable yields.

2.5.1 Sources of crop yield variability

Notwithstanding long-standing efforts at understanding these variabilities, there is not much consensus on the factors that underlie these geographical yield variabilities. Identification of sources of yield levels is not only necessary to explain current yield levels but to inform policy and programmes to improve future production (Lobell, 2013). Several studies (Assefa, Chamberlin, Reidsma, Silva, & van Ittersum, 2019; Niang et al., 2017; Ray et al., 2015; Reynolds et al., 2015; van Loon et al., 2019) have found a multiplicity of factors accounting for SSA's poor cereal productivity levels. Given that most of the maize cultivation in Ghana in particular, and SSA in general, is usually done under rainfed conditions, climate – precipitation, solar radiation, and temperature, among others – is often used to explain yield levels in the region (Niang et al., 2017; Snyder et al., 2016). At regional and agro-ecological scales, climatic factors have often been used to largely explain inter-annual yield variability (Górski & Górska, 2003; Hoffmann et al., 2018; Neumann et al., 2010; Ray et al., 2015). Indeed, other factors such as topographic indices and physical soil properties on yield variability still vary with climatic conditions (Chi, Bing, Walley, & Yates, 2009). This is particularly true for rainfed cropping systems in marginal agricultural regions where mechanization and associated farm management practices such as levelling are only applied to a limited extent. Ray et al. (2015), for instance, find that while some regions show no significant influence of climate variability on yields, in the majority of the major food producing regions, more than 70% of the maize yield variability is explained by climate variability with a complex interplay between precipitation and temperature variability being the main factors.

For instance, Niang et al. (2017) found that for rainfed farming systems, high rainfall and solar radiation, and low minimum temperatures are generally associated with high crop yields in West Africa. Interestingly, Kassie et al. (2014) find that as much as 60% of the variability in maize yields in Ethiopia is explained by variations in growing season rainfall while Srivastava et al. (2017) find that under prevailing nutrient regimes in Central Ghana, maize yields are not significantly correlated to precipitation during the growing season, but rather solar radiation and mean temperature during the season. The extent of crop yield variation on account of climate variability is highly location- and crop-specific (Kraaijvanger & Veldkamp, 2015; Ray et al., 2015). That is, the factors that underpin yield levels and variability differ depending on not only whether the region of interest is a core production region or a marginal one (Ray et al., 2015), but also on the measures taken to ameliorate the effects of too low/high precipitation and temperature such as irrigation (Neumann et al., 2010). Yield variability analysis on such scales are, however, of limited relevance to smallholder farmers who constitute the bulk of producers in SSA.

For smallholders, plot level variability is more relevant. While SSA farms, particularly smallholder farms, are generally noted for poor yields per hectare, there are significant plot-to-plot yield variations (Gregory & George, 2011; Mourice et al., 2015; Tittonell & Giller, 2013). At the plot levels, the most recurring yield determinants include soil fertility and inadequate application of fertilizers (Affholder et al., 2013; Dzanku et al., 2015; Mourice et al., 2015); insufficient or non-existent irrigations systems (Cheeroo-Nayamuth, Nayamuth, & Koonjah, 2011); imperfect agricultural markets (Frelat et al., 2016; Henderson et al., 2016); and poor access and adoption of technology (Laborte et al., 2012; Tittonell & Giller, 2013), among others. However, significant yield differences not only between but also within agro-ecological regions (Burke & Lobell, 2017; Dzanku et al., 2015; Farmaha et al., 2016) suggests that biophysical constraints such as climate and soils alone cannot explain poor crop yields and there is a growing consensus on this view (Mourice et al., 2015; Tittonell & Giller, 2013). The significant yield differences between and amongst even adjoining farm plots (Gregory & George, 2011) therefore point to other determinants at the micro level as being responsible for, or at least, contributing significantly to current yield levels. While several studies, including those reviewed here, adopt different approaches to categorizing the sources of yield variability, Beza et al. (2017) provides a more comprehensive review of the multiplicity of factors underpinning yield variability.

The above notwithstanding, a more straightforward dualistic categorization is one by Grisso, Alley, Phillips, and McClellan (2009), which groups the factors into those that result from smallholder management practices and those that are naturally occurring. The former include field history, soil compaction, water management, previous season's crop residue management among others, while the latter include weather, soil fertility, physical properties and water holding capacity, and pest infestations, among others. The authors posit that while natural sources of yield variability may not be under the direct control of farmers, the effects of these could be ameliorated with appropriate management practices. While the above dichotomy simplifies the factors driving yield variability, it is both largely arbitrary (and thus not exhaustive) and not generally adopted and applied. The strength of using this approach, however, is that it gives a clear indication of which factors fall within the control of farmers and those that do not. Given the significant effects that within plot variability in crop vigour has on yields (Masino et al., 2018), understanding the factors that underpin their presence is crucial to undertaking remedial activities on plots.

With regards to the first of these categorizations, certain management activities have been known to be associated with improved yield levels. For instance, differences in agricultural practices explained up to 36% of variations in rice yields across 22 sites in West Africa (Niang et al., 2017). Other less-often-considered management activities include land preparation prior to planting, and the control of pests and diseases. Average yields are usually higher for farms on which chemical fertilizers, animal droppings, and improved seeds have been used compared to those on which such management practices have not been undertaken (Dzanku et al., 2015; Yengoh, 2012). Beyond whether activities have been undertaken is the importance of the timing as well as the frequency of such management activities (Niang et al., 2017). With regards to sowing, for example, in addition to density, method, and intercropping status, the sowing date relative to the onset of rains has been found to have important implications for yield levels (Srivastava, Mboh, Gaiser, Webber, & Ewert, 2016).

In addition to input management, how the preceding season's crop residue is managed has been found to have important implications for yield levels, especially for farming systems in which there are limited application of inorganic fertilizers (Yengoh, 2012). Generally, straws are either taken from farm plots to be used as fuel, animal feed and roofing material or left on the farm. Where the former option is predominant, nutrients that would otherwise have been available to crops would have been extracted from the farm (Tittonell & Giller, 2013). Where the residue remains on the farm, they could be left in-situ and serve as mulching material. They could also be burnt either on the surface or underground or just buried and allowed to decompose to add to the organic matter content of the soil. Each of these management practices has varying impacts on yields. Yengoh (2012), for instance, finds that yields increase by as much as six folds – from 0.867 tons/ha to 6.283 tons/ha when the previous season's crop residue is burned underground compared to merely burying the residue. It is pertinent to note, however, that yields are further improved if such return of crop residue management activities are done in conjunction with chemical fertilizer application (Tittonell & Giller, 2013).

Furthermore, certain conventional management activities with regards to seed sources and varieties have important implications for yield levels. These include reliance on recycling or even borrowing seeds from neighbours to sow rather than use certified high-yielding varieties. In addition to such traditional practices, other emerging management practices also have potentially important implications for yield levels. This includes methods of weed control, particularly in the plot preparation and during the early stages of crop growth. The use of chemical and biological methods of weed control is becoming more widespread in addition to mechanical methods. While chemical methods of weed control help mechanize farming and make it less laborious and thus not too dependent on labour availability, there are concerns about their effects on crops and other biological organisms on farms (Krenchinski et al., 2018).

2.5.2 The underlying role of socioeconomic factors

While the extant literature frequently cites the challenges presented by socioeconomic dynamics, not many actually incorporate these into their analyses (Snyder et al., 2016). Where socioeconomic factors feature, they often relate to market access, level of knowledge of the farmer, availability of capital, infrastructure and institutional factors such as governmental support, extension services, and access to credit (Dijk et al., 2012; Neumann et al., 2010). Other areas that have not garnered the needed attention in the literature include factors that influence farmers' decisions such as risks, opportunity cost, land tenure, distances to plots and plots' location in the landscape, and the importance of non-farm income activities (Snyder et al., 2016). For instance, tenure systems in operation can, in diverse ways, contribute to farmland fragmentation and reduced fallows. These dynamics, together with limited inputs use, often lead to poor soil quality (Rurangwa et al., 2018). Reduced fallow periods in regions that predominantly practice shifting cultivation without adoption of higher-yield seed varieties and necessary management changes have led to significant stagnations in yields in the major maize production centres of Mexico (Ray, Ramankutty, Mueller, West, & Foley, 2012). *Article 3* of the thesis addresses the underlying role that land tenure plays in influencing not only farm management activities but also the nature and spatial distribution of within-plot crop variability.

Other important farm and plot characteristic such as plots' distance from homesteads and ownership also have important implications for yield levels. For instance, the motivations of farmers who outrightly own their farmlands and do not share crop output with others, might be different from those who rent and pay for the rented land with a proportion of the crop output with regards to willingness to invest in their farms. It is interesting to note that, on the one hand, the level of attention and resources devoted to plots closer to farmers' dwellings might be higher than for those plots further away (Munialo et al., 2019). Similarly, portions of plots closer to homesteads could benefit from nutrient dumping from household waste or more effective and efficient management compared to those further away from homesteads with regards to weed control and fertilizer application (Zingore, Tittonell, Corbeels, van Wijk, & Giller, 2011). The result is a situation where crops are more vigorous on sections closer to homesteads compared to portions further away from the homesteads. On the other hand, the relatively higher intensity of cultivation of farm plots closer to homesteads could lead to nutrient depletion over time.

Indeed, most determinants of crop yield levels are significantly influenced by the peculiar circumstances of individual smallholders. For illustration purposes, while poor soil fertility and weed control may be two important management factors influencing yield levels, they are often driven by low purchasing power (Affholder et al., 2013). As Mueller and Binder (2015) argue, yield determinants are as much sociopolitical and economic as they are environmental because the former influences farmer decision-making with regards to management practices and this, alongside local environmental conditions, determine the biophysical conditions crops experience during development. Yields from farmers' plots are part of a farm and a wider landscape system that is complicated by constraints that underlie them and shape farmers' decisions and ability to increase productivity (Snyder et al., 2016). Context-specificity is, therefore, important in this regard as smallholders' attitudes and perceptions are fundamental to their decision-making regarding on-farm investments and management activities (Moyo et al., 2012; Nigussie et al., 2017). The many and complex challenges that operate in any given situation vary over space and time (Harris & Orr, 2014). Indeed, Yengoh (2012) points out that yields can be significantly improved if interventions are tailored to specific constraints that confront smallholders at the local level rather than the usually generalized solutions often proffered to farmers. This tailoring must necessarily include not just farmers' choices and constraints, but also their perceptions and views, priorities, and decision-making. These are currently not given adequate attention in the literature on crop yields and their determinants and thus create an important research gap. *Article 4* addresses this gap by analysing perceptions and attitudes to the presence of poor patches on their plots.

2.6 Concluding remarks

Many studies that explain yield levels and their variability at the regional levels or between agro-ecological regions are useful in comparing the different regions and shedding light on the yield determinants at the various spatial scales. However, variability at the local level (community and farm levels and even within farm plots) is most germane to understanding poor yields and the constraints that smallholder farmers contend with. Understanding this is crucial to arriving at a holistic picture of the situation at the level most relevant to the farm and farmer. While yield variation and the factors that account for them are multiple and varied, they are also location- and crop-specific. Even within the same farm plots, different portions might exhibit poor performance for varying reasons. Thus, shedding more light on how and why these variations manifest at this scale, hold great potential for overall yield improvements particularly in the contexts of SSA.

Furthermore, a more comprehensive analysis of the spatial yield variability at the plot level could make seminal contribution to the well-known farm size-productivity debate with regards to whether there is the need to revise current methods of yield measurement, especially in developing countries. Current approaches of yield measurement using actual yields based on self-reports of outputs and farm sizes or crop-cuts come with several limitations as neither of these truly capture within-farm spatial variability. The remote sensing approach has the potential to tease out these intra-farm variabilities and revolutionize how yield levels in complex farming systems such as those in SSA are conceptualized. A shift from farmers' self-reported farm sizes to *the concept of effective farm sizes* has the potential to change our views on farm productivity in smallholder farms.

3 The theories

"There's nothing so practical as good theory" – Kurt Lewin, 1951.

3.1 Introduction

The present chapter discusses the theories that underpin this dissertation. Kurt Lewin's statement above is famous because a good theory should provide a reasonably consistent explanation for a phenomenon. Additionally, it ought to allow predictions to be made with a reasonable degree of reliability. In all, a good theory ought to be accurate, applicable, broadly-based, consistent – at least with itself and possibly with other accepted theories – evidence-based, falsifiable, and useful. Given the context within which social research takes place, there rarely is one theory that meets all these requirements for a study. Here, I discuss four theories and models that guide the study. For starters, I briefly discuss the Boserupian theory on agricultural intensification in the face of population growth and Chayanov's theory of the smallholder economy. Given the largely abstract nature of these theories, they may aptly be described as grand theories (Mills, 1959). As such, the arrangement and formal organization of concepts take precedence and trump the quest to understand social reality. However, taking a cue from the introductory quotation above, a good theory ought to be, above all, practical. I therefore also discuss the induced innovation theory (IIT) as put forward by Hayami and Ruttan (1985) and the sustainable livelihood framework (SLF) as developed by Chambers and Conway (1991) and further elaborated by DfID (1999) in order to ground my thesis by providing a bridge between the more abstract theoretical frame and the empirical parts of the dissertation. Thus, while the IIT helps to explain how agricultural development is proceeding in the study context, particularly with regards to technological development, the SLF helps conceptualize livelihoods in a holistic manner by capturing the many complexities of rural livelihoods. I then conclude the chapter with a framework that draws on all these theories to guide the study.

3.2 The Boserup theory of agricultural intensification

The core tenet of the Boserupian thesis holds that rapid population growth motivates the intensity of agricultural production (Boserup, 1965; Fischer-Kowalski, Krausmann, Mayer, & Schaffartzik, 2014). That is, as the population grows, food supply must grow to keep up with the growth in population. The growth in food production, through intensification, results from technological advancements in tools for farming as well as farming methods. There is also a feedback loop whereby technological advancement leads to further population changes (Boserup, 1981). The main driving forces of the evolution of farming systems towards higher productivity are thus population growth or density and market access – the latter depending on two factors: the external demand that emanate from the urban sector and exports markets, and infrastructure and transportation, which enable farmers to reach these markets (Binswanger-Mkhize & Savastano, 2017). Thus, in opposition to Malthus (1798)[10], Boserup (1965) reverses the direction of causality between population pressure and food production by arguing that increases in the former triggers the development or use of technologies and strategies to increase production commensurate with demand (Turner & Fischer-Kowalski, 2010).

Three broad types of agricultural intensification are distinguished by the theory. In the first scenario, the population growth of the territory remains very low. Of course, this cannot apply to the current context of SSA. In the second, high population growth leads to changes in the pattern of land use and in the kind of tools applied, accompanied by rising productivity in the non-agricultural sectors of the economy. The growth resulting from these other sectors contribute to improvements in the agricultural tools so that output per man-hours in agriculture increases (Boserup, 1981). In SSA, however, the second condition of growth in secondary sectors has not been achieved. That is, the manufacturing sectors of SSA countries have not evolved to be in a position to manufacture tools such as tractors at scales necessary for the

[10] The Malthusian theory has largely been disproved by history. Malthus's gloomy prediction did not materialize mainly because of the pivotal role that technological advancement played in improving agricultural production and productivity, particularly in developed regions. Even currently developing regions in which conditions, which led Malthus to make his predictions, persist have not experienced such dire consequence by virtue of the increasingly globalized system of world trade. However, the recent global food crises, which reached their zenith in 2008 and 2013, and the hoarding approach adopted by major grain producers suggests that reliance on global trade for national food security is not always prudent.

required growth in productivity in the agricultural sector[11]. Not only will this facilitate technological shifts but will also lead to more people depending on food purchases and having the financial means to do so. The third type of agricultural intensification entails a situation where population growth leads to changes in the patterns of land use and in the tools of agriculture while productivity in the non-agricultural sectors of the economy remains at a low level (Boserup, 1965, p. 65). What then results is the use of rudimentary tools despite the increasing population and increasingly intensive patterns of land use. This is the type of intensification that is proceeding in most parts of SSA.

In theory, thus, population growth and improved market access are expected to lead to agricultural intensification through a process whereby these forces lead to a reduction in fallow periods, accompanied by higher fertilizer use to offset declining soil fertility, and investments in mechanization. Binswanger-Mkhize and Savastano (2017), however, argue that population growth and market access are necessary but insufficient to lead to enough productivity growth to make contemporary farmers better off than their predecessors. Indeed, farmers can actually be economically worse-off through a process Geertz (1963) termed agricultural involution[12]. Such agricultural growth is dominated by labour intensification – driven by population growth – rather than by the adoption of technological innovation to meet growing market demand for food crops (Geertz, 1963). While not widespread, a few studies (Headey & Jayne, 2014; Lele & Stone, 1989) have found substantial evidence of agricultural involution occurring in some parts of SSA.

Furthermore, Boserup's theory posits that simple societies with a sustained population growth have a better chance of getting into a process of genuine economic development than similar societies with stagnant or declining populations (Boserup, 1965, p. 106). It, however, has two important caveats to this postulation; first, such communities must not already have very high rates of population growth or be already densely populated, and second, such communities should be able to undertake significant investments necessary for introducing still more intensive methods of agricultural cultivation. That is, in

[11] Given how increasingly globalized the world economy is, individual countries would not need to produce their own, say, tractors. The more relevant technologies in this context is the appropriate methods and levels of improved seeds and fertilizers.

[12] The term involution, coined by anthropologist Alexander Goldenweiser, describes a culture that, in reaching a definitive form, does not adapt and evolve further but only develops unidirectionally in internal complexity and without efficiency; a semblance of change without substantive change (Hui, 2009). Agricultural involution, thus, describes an increase in productivity per hectare but without an accompanying economic increase per capita, leading to a cycle of poverty and static opportunity (McCullough, 2019; Geertz, 1963).

contexts of rapid population growth in a pre-industrial economy, farmers must not only be able to adapt themselves quickly to new methods – even if these have been used for millennia in other parts of the world – but must somehow, be able to bear the burden of a high rate of investments as well as undertake sweeping changes in land tenure (Boserup, 1965, p. 54). Thus, two key concepts in the Boserupian thesis relevant to the present study are investments in agriculture and land tenure. Smallholders would shift to investing in newer technologies and managerial innovations only if land and labour dynamics pressured them to do so (Turner & Fischer-Kowalski, 2010). This is in line with the assertion of Schultz (1964) that it does not pay to invest in the type of farming capital that is already in existence on traditional farms and that smallholders will have to be incentivised to adopt modern factors.

The classical economists' views on the effects of population growth on agriculture assumes that private ownership of land emerges when agricultural lands become scarce under the pressure of growing numbers of people (Boserup, 1965, p. 68). That is, agricultural land would remain free for everybody to access and use as desired, as long as the population in a given territory was small. This view however oversimplifies a rather complex phenomenon of land availability. For one, land would not be equally available to different type of cultivators. For instance, while farmlands may be scarce for shifting cultivators whose cultivation methods require long fallows, farmland may appear to be in abundant supply for more intensive farmers. An important consequence of growth in population is the gradual disappearance of general rights to farmlands and emergence of private ownership. This often leads to shortening of fallows and gradual penetration of monetary transactions in villages; a process connected to the degree of urbanization. Much like what currently obtains in the property ownership in many developing countries in SSA, the theory posits that, at such stages of population growth and agricultural development, land is considered the private property of landlords who then claim rents not determined by custom but by the markets, and so have the liberty evict to smallholder tenants whenever they please (Boserup, 1965, p. 77).

The theory postulates three main stages that can evolve in the face of growing population in rural communities (Boserup, 1965, pp. 78-79). First, long-fallow smallholders, in order to cope with increasing population, undertake additional land clearing to make land improvements for the changeover to more intensive systems of land use. This is, perhaps, more practical in a context where general rights of cultivation persists so that private rights to cultivate particular plots have not yet resulted in a situation whereby all families or farming households permanently occupy specific plots. Second, an agrarian community in which growing populations must create additional arable fields for short-fallow cultivation or invest in other types of land improvements in order to be able to crop existing arable land more frequently. The relevant assumption about the land tenure here is that each smallholder family permanently occupies given plots of arable land. However, feudal tenure does not inhere in much of the contemporary world. The third is where modern tenure predominates, and most smallholders rent the land and then pay money for not only agricultural labour but also the purchase of non-agricultural consumer goods while they continue to use little or no industrial input in agriculture. It is this third stage that is of relevance in the current context. As the theory itself points out, as long as the economy to which such a community belongs is at a low stage of industrialization, agriculture is unlikely to use more than insignificant quantities of industrial inputs. Besides, nearly all private investments in agriculture is likely to be undertaken by local labour and with rudimentary tools (Boserup, 1965, p. 91). This creates a problem because already limited resources will have to be prioritized based on the needs and judgments of the smallholder household. Smallholders and their capabilities and decision making then become crucial in terms of the prospect of the growth rate of the agriculture system (Schultz, 1964).

To recap, the core arguments of Boserup's theory are that population growth increases population density and this in turn necessitates finding ways to use land more intensively. This process of intensification often entails multiple annual cropping and reduced fallows. At any point in time, depending on the composition of the household and the stage of economic development of the society concerned, two different effects of increasing population density will prevail. On the one hand, it can lead to making life easier by virtue of sharing of the burden of accessing natural resource. In this context, the increase becomes an asset for the household, especially where members are of the productive age group. On the other hand, and especially in the long term, the ratio of natural resources to the population decreases. Thus, an increase in population density, using either of these tendencies, provides incentives to replace natural resources which would become scarcer with labour and capital. The process is thus significantly influenced by the dynamics in the smallholder household.

3.3 The Chayanov theory

Although the Chayanov's theory of the peasant[13] economy was propounded based on a particular set of features of the Russian agrarian system[14], it is applicable to other contexts where smallholders rely almost exclusively on family labour and operate within a partially monetized economy (Hammel, 2005). The crux of the Chayanov theory is that the family farm is setup to satisfy locally acceptable standards of consumption and that once this is achieved, the 'self-exploitation' of the smallholder household ceases. That is, the Chayanovian farm household is a production and subsistence unit whose workers expend effort only necessary to provide for the consumption needs of all members (Hammel, 2005; Netting, 1993)[15].

The central concept of the Chayanov theory is termed the *labour-consumer balance* between the satisfaction of family needs on the one hand and the drudgery of labour on the other hand. Chayanov opines that each smallholder household seeks an annual output adequate for its basic needs but since this involves drudgery, the household would not push its work beyond the point where the possible increase in output is outweighed by the drudgery of the extra work (Chayanov, 1966). The theory then posits that for each smallholder household, the balance between consumer satisfaction it requires and the degree of drudgery it would tolerate is affected by the family size and the ratio of economically-active to economically-inactive household membership. Thus, although Chayanov examines the collective effects of a host of factors such as size of landholdings, quality of soils, crops grown, location, markets, interest rates, relative population density, and availability of off-farm work, among others, on the labour-consumer balance, the main focus was the family size and composition. That is, while most smallholders may be in a position to

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[13] My thesis focuses on smallholders who can be seen as a sub-group of peasants; while the former have access to land – either rented or bought - for their own holdings and relying almost exclusively on family labour, the latter also includes farm labourers who may not have a holding of their own.

[14] These features include land abundance, long-fallow cereal cultivation, periodic reallocation of fields at least in some communities, relatively sparse rural population and a system of serfdom whereby workers had little access to markets. Netting (1993) argues that the Chayanovian theory of smallholder economy suffers from poorness of fit for most intensive cultivators because these features rarely inhere in contemporary times.

[15] In this regard, the ideas of Boserup (1965) mirrors those of Chayanov (1966) – although the former had not read nor heard of the latter at the time of postulating her theory – regarding the differences in behaviour and attitudes between subsistence and commercial farmers (Turner & Fischer-Kowalski, 2010).

work more hours or more intensively – self exploitation – they would only do so if they had reason to believe that would yield an increase in output, which could then be devoted to greater household consumption, increased investment on the farm or both. This way, the available income was usually divided according to the equilibrium of production and consumption evaluations based on a motive to maintain a certain constant level of wellbeing. This determination is done based on the subjective judgments of household heads using their long experience of current and previous generations – accumulated indigenous knowledge. This rational and optimizing attitude and behaviour in smallholders of their personal and household welfare is a response to market imperfections as well as to their own estimated production and consumption needs (Netting, 1993). It is within this context that they would increase their per capita labour sufficiently to feed household members while minimizing the drudgery this entails.

Developing a nuanced understanding of smallholders and the economics of their household is key to dealing with some of the most important challenges confronting agriculture in developing countries. Chayanov posits that the surest way to misunderstand the smallholder family farm was to view it as a business enterprise of a capitalist sort (Chayanov, 1966). To him, the primary preoccupation of a capitalist enterprise is profit making and maximization and this would necessarily require the use of hired labour. In the definition of Chayanov, however, smallholders employed no hired labour and depended almost entirely on household labour. Chayanov then argues that in the absence of the use of hired labour, smallholders' behaviour cannot adequately be accounted for by conventional economic theorisations, which rely on wages (of labour), interest (on loans and capital), rent (for land), and profits (of enterprises). Given that these factors of production operated in close functional interdependence and are reciprocally determined, the absence of one – wages for example, implies that others could not be precisely worked out. Chayanov also saw no validity in circumventing this shortfall by imputing values to unpaid family labour. The main argument here, therefore, was that the behaviour of smallholders could not be accounted for adequately using standard economic theories.

On the question of the viability of smallholder family farms, Chayanov also posits that certain fundamental characteristics of family farms make them more enduring beyond the point where capitalist-oriented counterparts would go bankrupt (Chayanov, 1966). These characteristics include the price they are willing to pay for land, interest they are willing to pay on borrowed capital, price they are willing to sell their farm produce, among others. Thus, at the point where market-oriented farms would become insolvent, smallholder households could work longer hours, sell produce at lower prices, obtain no net surpluses, and yet continue to manage their farms. This view of smallholder viability is in direct opposition to the mainstream, Marxist view of the time, which held that:

> "…{the} *peasant who produces with his own means of production will either gradually be transformed into a small capitalist who also exploits the labour of others, or he will suffer the loss of his means of production…and be transformed into a wage worker. This is the tendency in the form of society in which the capitalist mode of production predominates"* – (Marx, 1951, p. 194).

This Marxian view of the prospects of the smallholder farm concurs with that of the modernisation theory espoused by Walter Whitman Rostow (Rostow, 1960), which essentially posits that technological advancement would inexorably replace traditional, stagnant subsistence farming and free up excess rural labour for the more productive urban industrial sectors of a modernizing economy. This was in contradiction to the findings of Kautsky (1899) that German smallholders were not being ousted in the manner outlined by Marx. Instead, smallholders were able to sustain their incomes through part-time work for larger farms while keeping their own lands (Brookfield, 2008). Alternatively, the increased demand of household members for more subsistence food is met by enlarging farm size or cropped area (Netting, 1993). This alternative is, however, limited in societies where the land tenure system is significantly changed so that private ownership and relative land-scarcity put the cost of rent beyond the means of most smallholders.

While the Chayanovian theory was originally propounded with a particular type of family farm in Russia in mind, it bears wider application in contemporary times in other regions of the world where similar kinds of smallholder systems predominate; namely SSA (Netting, 1993). However, Chayanov himself gave three important caveats for the applicability of the theory: first, that the theory would work better in sparsely populated countries than in densely populated regions; second, that the theory would work better in countries that have had their agrarian structure shaken up than in countries with a more rigid agrarian structure; and third, that the theory would need substantial modification in regions where smallholders could not readily buy or take in more lands. In the light of the population dynamics and the agrarian structure of much of SSA, the Chayanovian theory would require important revisions, especially regarding land tenure, to be applicable in contemporary SSA. The main challenges in the application of the theory to much of SSA stems from its characterization of smallholders as in the context of land abundance, self-sufficiency, little commodity production or marginal market participation, and non-utilization of hired labour (Netting, 1993, pp. 310-311).

Following from the discussions in the last two sections, Boserup's theory on agricultural intensification in the face of population growth and Chayanov's theory of the peasant economy, being grand theories, have served the useful purpose of giving us a global perspective on smallholders and how their agricultural development proceeds. A common criticism often levelled against Boserup is the secondary role she assigns to inputs such as fertilizers, pesticides, and herbicides as well as tools and their improvement in agricultural development. Thus, despite their usefulness, they are limited in certain important ways and their shortfalls can be overcome with more practical theories. In the next two sections, I present the more applied induced innovation theory and the sustainable livelihoods approach.

3.4 The model of induced innovation

The term 'induced innovation' was first used by Hicks (1932) to reference the changes in factor prices brought about by biases in the direction of technical change, which save progressively more expensive factors. Hayami and Ruttan (1985) use this concept to postulate their model of induced innovation. The model of induced innovation provides insights into the process of agricultural development for both developing and developed countries (Otsuka & Runge, 2011). It is the result of the integration of five general agricultural development models: the frontier, conservation, urban-industrial input, diffusion, and high-payoff input models into a single, more complete model of agricultural development (Ruttan, 1977). The model thus explains the pathways through which both technical and institutional changes influence agricultural development when the two are treated as endogenous to the development process in the face of changes in factor prices. In this sense, the changes in factor prices induce certain innovations by substituting more expensive factors of production for less expensive ones. From the Boserupian perspective, scarcity, instigated mainly by population increase, induces growth in agricultural production through intensification and extensification (Binswanger-Mkhize & Savastano, 2017; Boserup, 1965). The trajectory of agricultural development in SSA demonstrates that population and markets are necessary but insufficient to occasion adequate levels of on-farm investments. For a country like Ghana, growth in land productivity, driven by new and improved technology, is *sine qua non* for the development of the agricultural sector. I argue, therefore, that the induced innovation model more comprehensively explains how technological innovations proceed in SSA.

The crux of the induced innovation hypothesis is that a common basis for achieving rapid growth in agricultural productivity is the capacity to generate an ecologically-adapted and economically-viable agricultural technology in country or development region (Hayami & Ruttan, 1985; Ruttan, 1977). The hypothesis further holds that achieving continued productivity growth over time involves a dynamic process of adjustment to the original factor endowments and to resource accumulation processes over time. That is, cultural, political, and economic *institutions* need to dynamically respond to the growth potential that is created by new technological alternatives. Prior to the postulation of this theory, the mainstream view was that agricultural technology was exogenous[16] to the economic system. However, the seminal works of Ruttan (1977) and Hayami and Ruttan (1985) show that the causal sequence leading to the inducement of technological innovations starts with a change in relative factor scarcities, which in factor markets reflects in changes in relative factor prices, which in turn define the optimal technological bias from farmers' perspectives. Farmers then convey their needs through collective action to scientists and engineers. The latter group then responds by developing and making available new technical breakthroughs and new inputs that would enable farmers to replace more expensive factors with less expensive ones to their advantage. The authors posit that it was through this process that optimal technological advances could be guaranteed to farmers.

The model, as illustrated in **Figure 3.1** below essentially comprises four main interacting components: resource endowments, technology, institutions, and cultural endowments, in pattern relationships. An important advantage of this pattern model is that it helps to identify which of these relationships have been well-developed and those that have more potential for development. For example, while the capacity to model and test the relationship between resource endowments and technical change (A) is relative strong, that between cultural endowments and either technical (E) or institutional change (C) is relatively weak (Hayami & Ruttan, 1985).

These four components are intricately intertwined in a recursive multicausal relationship and in an open systemic way although in any given context, the different elements have differing levels of importance and influence. Cultural endowments (such as religion, ideology and tradition), for example, could

[16] The exogeneity implies that it is exclusively a product of scientific and technological advancement. With the IIT, however, technical, and institutional changes are treated as endogenous to the economic system.

exert enormous influence by making some form of institutional innovations less costly to establish while imposing severe costs on others (Hayami & Ruttan 1985). Pre-existing traditional patterns of cooperation represent an important cultural resource on which to erect modern forms of cooperative marketing and joint farming activities. For example, in the present study area, there is a tradition of farmers cooperating to prepare land for maize planting. This, together with the moral obligation inherent in communal labour activities, locally called *asafo adwuma,* could be harnessed to implement rural development projects such as maintenance of agricultural roads and irrigation facilities. These cultural endowments which encourage cooperation are, however, waning in popularity and giving way to specialization and individualization The sterling analytical prowess of this structure is demonstrated by Kikuchi and Hayami (1980) in their study of the impact of population growth and technical change on changes in labour markets and land tenure in the Philippines.

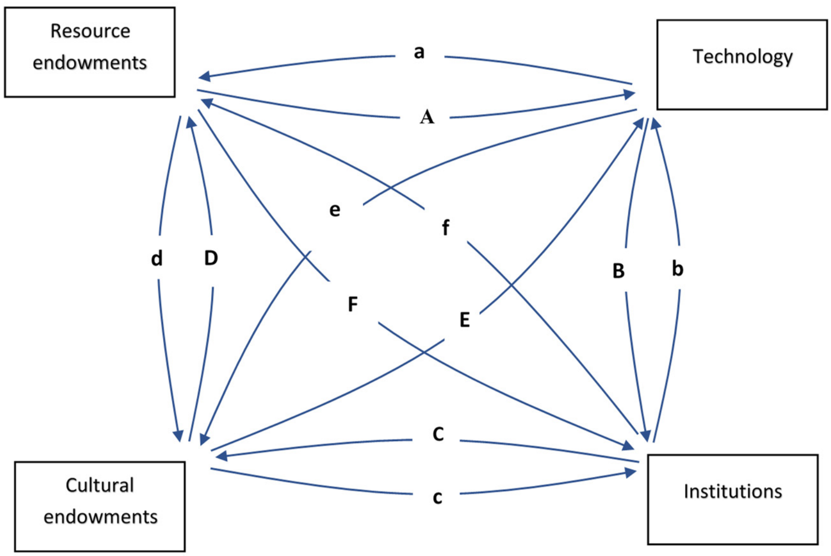

Figure 3. 1: A more complete induced innovation model showing the interaction between resource endowments, technology, institutions, and cultural endowments
Adopted from Hayami and Ruttan (1985, p. 111)

Thus, rather than view it as a linear process so that new knowledge is applied to the production process and if found to be economically successful, diffused through the process of imitation to others[17] (Knickel, Brunori, Rand, & Proost, 2009), the model above shifts the focus from adoption to institutions, cultural and resource endowments as sources of technical change. The model, thus, demonstrates that shifts in the demand for institutional innovation are induced by changes in relative resource endowments and by technical change as well as advances in social science knowledge and cultural endowments. Institutions, being the rules of society that facilitate coordination among people by helping them to form expectations of each other (Otsuka & Runge, 2011), reflect conventions that have evolved and been established in different societies. In economic relations, institutions have a crucial role in establishing expectations about the rights to use resources and thus ensure stability and order in an uncertain and complex world. Relevant examples of institutions in this study include property rights, extension services, and markets. Institutions such as extension services whose primary mandate is to drive change can indeed become barriers to innovation if they do not recognize and acknowledge that the needs of farmers and society have changed (Knickel et al., 2009).

Cultural endowments include traditions and religion as well as ideology in the form of nationalism (Otsuka & Runge, 2011). Cultural endowments strongly influence the supply of institutional innovation by making certain forms of institutional change less costly to establish while imposing severe costs on others. Traditional patterns of cooperation, for example, represent an important cultural resource on which modern forms of cooperative marketing and joint farming activities can be erected (Kikuchi & Hayami, 1980).

Industrialization interacts with agricultural development in complex ways. Growth in agricultural productivity entails a process of adaptation of the agricultural sector to new opportunities created by the advances in knowledge and by the progress of inter-industry division of labour, which accompanies industrialization. Variations in labour and land productivity among countries are associated with differences in the levels of industrial input, which then ease the constrains imposed by the inelastic supply of primary factors of production (Hayami & Ruttan, 1985). As mentioned earlier, technological innovations in agriculture tend to be induced by changes in relative factor scarcities – resource endowments – which in factor markets reflects in changes in relative factor prices. Such changes in factor prices can then induce the development of technology to facilitate the substitution of relatively abundant and hence cheaper factors for relatively scarce and hence more expensive factors of

[17] Based primarily on the conventional neo-classical behavioural model, this linear view tends to focus on adoption so that emphasis is usually on understanding why, given certain available innovations, adoption rates are much lower than expected.

production (Ruttan, 1977). While the new technology – be it in the form of new crop varieties, new equipment or new farming practice – may not always directly substitute for land or labour, they may serve as catalysts in facilitating the substitution of relatively abundant factors such as fertilizers for relatively scarce ones such as land and labour. Lower prices of fertilizer and labour relative to those of land should, thus, result in priority being placed on land-saving intensification practices, which utilize more fertilizers.

An important caveat here, however, is that the agricultural sector must be able to adapt to the new set of factors and product prices (Hayami & Ruttan, 1985). This adaptation involves not only the movement along a fixed production surface but also the creation of a new production surface that is optimal for the new set of prices. For example, even if fertilizer prices decline relative to the prices of land and farm products, increases in the use of fertilizers is not guaranteed unless new crop varieties are developed that are more responsive to high levels of biological and chemical inputs than the traditional varieties.[18] It is, thus, rational for farmers in economies in which prices of fertilizers are relatively low and agricultural produce relatively high to cultivate varieties that are responsive to higher levels of fertilization and to fertilize more. It is equally rational for farmers in countries with relatively high fertilizer prices and relatively low agricultural produce prices to rely on traditional varieties and use limited levels of fertilizer. In the light of this, the poor performance of the Green Revolution technologies – the development and diffusion of modern semi-dwarf varieties of rice, wheat, and maize with high fertilizer-absorbing and high-yielding capacity – in SSA can largely be explained by the induced innovation model.

Using the IIT, thus, explains how innovations such as fertilizers, herbicides, and improved seeds are induced and adopted in different economies and societies. It also explains the logics behind farmer decision-making in rejecting or adopting these innovations. It is important to note, however, that even within the same societies and villages these adoption processes proceed in a complex manner. Different households with differing capabilities, assets and resources respond differentially to innovations that are introduced to entire villages. This, in turn, leads to differential yield outcomes on their farms. The next section, using the sustainable livelihood approach, discusses these processes.

[18] Traditional crop varieties are, by themselves, an efficient technology developed over a long period of time through a process of trial and error by farmers in an environment of high fertilizer prices relative to product and other input prices.

3.5 The sustainable livelihood approach

The seminal work of Chambers and Conway (1991) for the Institute for Development Studies is often referenced as ground-breaking for the sustainable livelihoods approach (SLA). It laid the foundation for many other important works in this area including those of (Scoones, 1998), Bebbington (1999) and DfID (1999), among others. The livelihoods approach partly traces back to literature concerned with understanding the differential capabilities of rural households to cope with crises such as floods, drought, or plant and animal pests and diseases infestations (Allison & Ellis, 2001). The approach offers an important lens for analysing complex rural development problems. At the core of it, there is commitment to locally-embedded contexts, place-based analysis and poor people's perspective so that understanding local contexts as well as the views and aspirations of the marginalized become central to rural research (Scoones, 1998). It, thus, offers a unique starting point for an integrated analysis of dynamic and complex rural settings.

The sustainable livelihood framework (SLF) provides a template for understanding and analysing livelihoods in this approach. The SLF – **Figure 3.2** – put forward by the UK's Department for International Development (DfID) provides a most comprehensive analytical structure to facilitate a broad and systematic understanding of the many complex factors that constrain and enhance livelihood opportunities and how these relate to others (Krantz, 2001). The opportunities and constraints that households contend with on a daily basis are shaped and influenced by an array of forces emanating from both global and local structures and systems (DfID, 1999). From the global scale, individual households are often neither aware of nor have any semblance of control over such forces. At the local level, households are affected by culture, norms and institutions, which shape their livelihoods in important ways.

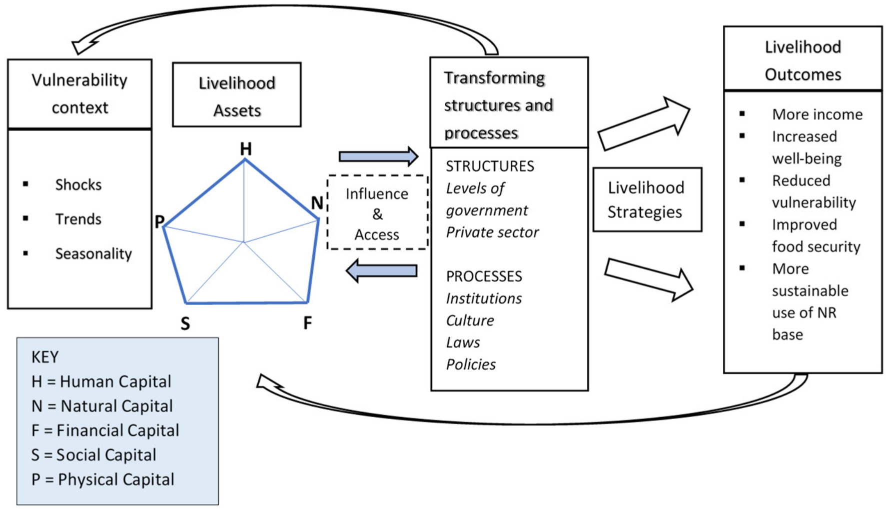

Figure 3. 2: The Sustainable Livelihood Framework
Adopted from DfID (1999, p. 3)

As **Figure 3.2** above shows, livelihoods are shaped by a dynamic range of forces and factors. These key factors and forces require, at least, some brief explanations in order to fully understand how they influence and shape livelihoods. While the SLF begins with the vulnerability context box, it is more intuitive to grasp it from the transforming structures and processes box given the latter's overarching importance to the whole framework. Transforming structures and processes encompasses institutions, organizations, policies, and legislation as well as laws, culture, customs, and traditions, which operate at all levels and spheres and shape livelihoods (DfID, 1999). They, thus, determine access to various forms of capital, terms of exchange between different types of capital as well as returns to any given livelihood strategy. More importantly, and as the SLF shows, transforming structures and processes has a more direct relationship to vulnerability contexts. The vulnerability context frames the external environment in which people live (DfID, 1999). Vulnerability denotes the degree of exposure to risks (such as effects of climate change), shocks (such as crop and livestock loss through pest and disease infestation), trends (such as population and technological trends), stresses, and seasonality – in price and production levels (Allison & Ellis, 2001). The factors that make up the vulnerability context are critical because they tend to have more direct impacts on individual and households' assets and the options open to them in their pursuit of meaningful livelihoods (DfID, 1999).

The asset pentagon[19] lies at the core of the SLF given the people-centred perspective of the SLA. Assets denote the resources and endowments that individuals and households rely on to construct livelihoods for themselves (Bebbington, 1999; DfID, 1999). Within the SLF, five main categories of assets are identified: human assets (skills, knowledge and labour or the ability to command labour); natural assets (land, forests, water, and erosion protection, among others); financial assets (available stocks such as savings as well as liquid assets such as livestock and jewellery, and regular flows of money through, say, pensions or remittances); physical assets (infrastructure such as roads and machinery such as knapsack sprayers); and social assets (through networks and connectedness, membership of formalised organizations, and relationships of trust and reciprocity). The crux of the SLA is that people require a range of these assets to achieve positive livelihood outcomes and that no single category of asset would suffice to meet the many and varied outcomes that people strive for (DfID, 1999). Livelihoods are, thus, constructed using physical labour, creativity, skills, and knowledge. The latter two may be acquired within a household and passed down from one generation to the other as indigenous technical knowledge, or through apprenticeship or through more formal education, extension services or through experimentation (Chambers & Conway, 1991).

The transforming structures and processes interact with livelihood assets in complex and dynamic ways through influence and access (DfID, 1999). The latter refers to the opportunity in practice to use a resource, store, or service, or to obtain information, material, technology, employment, food, or income. While certain services such as roads as a means of transport, or markets may be publicly available, others such as access to information may be obtained by investing in radio or education (Chambers & Conway, 1991). More important, access also entails the right to common property resources such as use of state or communal lands for fuelwood or agricultural production. Bebbington (1999) posits that of, all the resources available to individuals and households, the most critical is access. Livelihood strategies encompass the range and combination of activities and choices that people undertake in order to achieve their livelihood goals. While livelihood strategies that people adopt are intricately linked to their objectives, the differential levels of access and

[19] Sometimes, a sixth asset – cultural asset – is distinguished and defined as the behaviours, values, and knowledge transmitted between and among people in a community (Dyer & Poggie, 2000)

combination of assets play major roles in their choices of livelihood strategies (DfID, 1999). Furthermore, while some livelihood strategies may be ascribed by the accident of birth, others are the result of improvisation due to desperation so that what an individual adopts as a livelihood strategy is determined by the social, economic and ecological environment in which they find themselves (Chambers & Conway, 1991, p. 6). For example, while a farmer's child is likely to inherit farmlands and tools and thus become a farmer themselves, education and migration could widen the choices available to such an individual.

The outputs or end results of livelihood strategies are livelihood outcomes. Livelihood outcomes range from more income, improved well-being, reduced vulnerability, improved food security to more sustainable use of the natural resource base. These livelihood outcomes can be mutually exclusive so that the achievement of one, say more income, could be inimical to the attainment of another – sustainable use of the natural resource base. Furthermore, it is important to understand people's priorities and motivations and not assume that people are always entirely dedicated to maximizing their production or incomes (DfID, 1999). To this end, studies that employ the SLA must necessarily incorporate local perceptions and knowledge (Krantz, 2001). As the SLF shows, there is a direct feedback loop between livelihood outcomes and livelihood assets. That is, a person may opt to reinvest most or all their increased incomes in order to acquire new assets, which will then serve as a catalyst to propel that individual into a virtuous cycle of asset accumulation and more income. For example, a smallholder who produces more and receives better prices for his/her farm produce might invest the additional income in a knapsack sprayer. Such a farmer will then be in position to expand their production capacity, which then translates into further increased income.

It is all encapsulated by the concept of sustainability, defined as that which meets the needs of the current generation without compromising the ability of future generations to meet their own needs (WCED, 1987). Defined this way, sustainability can be applied to any endeavour to indicate endurance in the long term. In livelihood studies, sustainability is a function of how the different categories of assets are utilized, maintained, and/or enhanced to preserve livelihoods in the long term. In this usage, Chambers and Conway (1991) distinguishes two facets of sustainability: environmental sustainability and social sustainability. The former concerns a livelihood's external effect on local and global resources and assets while the latter concerns a livelihood's internal capacity to withstand outside pressures and retain its ability to continue and improve. Chambers and Conway (1991) thus, regard livelihood activities that have a net negative effect on the claims and access needed by others as environmentally unsustainable. The weakening of access and claims of others can occur by law, force or through bureaucratic bottlenecks. For example, access to communal lands can be diminished through expropriation by state bureaucracy through the instrument of the law. Being largely intrinsic, social sustainability depends on the dynamic competence of the individual such as one's ability to not only perceive or predict but also adapt to and exploit changes in their surroundings (Chambers & Conway, 1991). Possession of such competence can mean that a smallholder family's livelihood can become more sustainable even in uncertain conditions when markets and prices fluctuate. In this regard, the concept of resilience – the ability of a livelihood system to bounce back from shocks and stresses – becomes relevant (Allison & Ellis, 2001).

The oft-used definition of sustainable livelihoods by Chambers and Conway (1991) has thus been modified by Scoones (1998) as follows:

> "A livelihood comprises the capabilities, assets (including both material and social resources) and activities for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks, maintain or enhance its capabilities and assets, while not undermining the natural resource base" (p.5).

A sustainable livelihood must therefore have the ability to avoid, or more likely, withstand and recover from shocks and stresses (Chambers & Conway, 1991). The livelihood approach thus engenders a more holistic understanding of the smallholder economy and of how the smallholder households make a living given the specific constraints and opportunities that confront them on a daily basis. It, thus, centres on the linkages between individual and household assets, the activities in which households can engage in with a given asset profile and the role of mediating processes – institutions and regulations – that govern access to assets and to alternative activities (Allison & Ellis, 2001). The livelihood perspective thus offers a unique starting point for an integrated analysis of complex, and dynamic rural contexts (Scoones, 2009). Rural livelihoods should therefore be understood in terms of (a) people's access to five capital assets; (b) the ways in they combine and transform those assets into building their livelihoods that, as far as possible, meet their material and experiential needs; (c) the ways in which people are able to expand their asset base; and (d) the ways in which people are able to deploy and enhance their capabilities both to make a living more meaningful as well as to change the dominant rules governing the ways in which resources are controlled, distributed and transformed in society (Bebbington, 1999). As Scoones (1998) succinctly puts it:

> "Given a particular context (of policy setting, politics, history, agroecology, and socioeconomic conditions), what combination of livelihood resources (different types of capital) result in the ability to follow what combination of livelihood strategies (agricultural intensification and/or extensification, livelihood diversification, and migration) and with what outcomes? Of particular interest in this framework are the institutional processes (embedded in a matrix of formal and informal institutions and organizations) which mediate the ability to carry out such strategies and achieve or not such outcomes" (p. 3).

Households with some appreciable level of access to various categories of capitals have the possibility to adapt their livelihood strategies so that even in adverse conditions they are not unduly affected negatively. They are able to adapt their livelihoods in order to *hoard* through accumulation of food and other assets and *protect* their asset base. Those without such possibility tend to only cope through *stinting* by reducing current consumption levels or shifting to lower quality of food, *depleting* remaining assets or household stores of food, *diversify* by seeking new sources of food or spreading work activities and income sources especially during the off-season, or by making *claims* on relatives, friends, neighbours, patrons, the community, among others by calling in debts and favours, begging, appealing to reciprocity and goodwill (Chambers & Conway, 1991, p. 11). Herein lies the fundamental difference in the livelihood outcomes that are possible for different groups of households with varying capital bases. The degree of specialization relates to the resource endowments available and the level of risk associated with alternatives (Scoones, 1998, p. 10). The inherent fragility of the livelihoods of the most vulnerable reduces their ability to cope with stress and shock, predictable or not (DfID, 1999). That is, even when trends move in predictable trajectories, the poorest are unable to benefit due to lack of assets and strong institutions working in their favour. To reverse this situation, priority needs to be given to the capabilities, assets, and access of the poor. This entails some practical steps such as redistribution of tangible assets such as land; securing rights to land, water, trees, and inheritance to children; protection and management of common property resources and equitable rights of access for the poorer and less-powerless; enhancing the intensity and productivity of resource use; and right and effective access to services, especially education, health and credit (Chambers & Conway, 1991, p. 23).

Having been at the forefront of development policy and practice for more than a decade, the SLA came under criticism for some shortcomings. Scoones (2009, pp. 181-182) highlights four of the most discussed failings of the livelihood perspective. The first relates to its inadequate engagement with processes of economic globalization. This criticism is often framed as the SLA being overly focused on the micro-level and neglecting the macro level forces. While this criticism has some substance given the preoccupation of the approach with what is local, the SLF makes provisions for forces and politics beyond the local in the transforming structures and processes box and how this influences vulnerability contexts at the local level. The second weakness of the SLA relates to the neglect of power dynamics, especially as they relate to gender. For instance, while social capital – connections and connectedness to more powerful people in society – tend to be viewed as positive, in practice it can be inclusionary or exclusionary; often with the poorest being excluded and disadvantaged. Even for those socially connected, the hierarchical nature of such relationships implies that they are potentially coercive and exploitative for those at the lower levels. Even for reciprocal and horizontal relationships, obligations can be onerous (DfID, 1999), especially in times of stress and shocks.

The third criticism relates to the lack of rigorous attempts to deal with long-term secular changes in environmental conditions. Despite co-opting the term 'sustainable' in its name, the SLA has been criticised for not adequately dealing with possibly the biggest issue of the 21st Century: climate change. In the livelihoods discourse, sustainability tends to be associated with coping with immediate shocks and stresses for which building up local capacities and knowledge would suffice (Scoones, 2009). This, however, fails to adequately deal with the broader issues of climate change given that the most vulnerable to its impacts are the poor. The fourth criticism relates to the SLA's failure to adequately engage in debates relating to long-term shifts in in rural economies and the broader question of structural and agrarian change. While processes of de-agrarianization (Bryceson, 1996) and of livelihood diversification (Ellis, 2000) have been ongoing for a while now, there is growing evidence of their increasing momentum in more recent times (Andersson Djurfeldt et al., 2018; A. A. Djurfeldt & Djurfeldt, 2013; Jirström et al., 2018). Going forward, an important challenge of the SLA will thus be integrating livelihood thinking and understanding of local contexts and responses with concerns for global environmental change and the processes of diversification and deagrarianization (Scoones, 2009).

While these limitations of the SLA are valid, the approach carries with it certain fundamental principles – the centrality of people and their context as well as special focus on the capabilities and capacities of the marginal in society (Scoones, 2009). Adequate and sustainable livelihoods is a common aspiration of the poor and so their involvement in the processes empowers and prioritizes their perspectives and perceptions of the kind of livelihoods they need and want to work towards (Chambers & Conway, 1991).

3.6 Linking the theories – towards a more holistic view

Thus far in this chapter, I have reviewed two more abstract, grand theories: the Boserupian theory of agricultural intensification and the Chayanovian theory of the smallholder economy. In order to ground my study, I have also discussed the induced innovation theory and the sustainable livelihood approach. Both Boserup (1965) and Hayami and Ruttan (1985) focus on the technological changes and investments induced in agriculture by a rapid population growth and the implications of the latter on the transition from a communal to private land ownership and agriculture develops from these processes. The changing dynamics in farmland abundance/scarcity and tenure security have important implications for farm households' willingness and motivations to invest beyond the point where minimum consumption needs are met (Chayanov, 1966).

There are similarities and complementarities between and amongst the theories used here. In terms of similarity, both Boserup (1965) and Chayanov (1966) are fundamentally in agreement that smallholders respond more to household consumption than market demands and tend to seek to minimize household needs rather than maximize gain (Turner & Fischer-Kowalski, 2010). Given the level of income poverty among smallholder households and the non-pursuit of profit maximization, it is often tempting to conclude that they are inefficient and irrational. However, as has been demonstrated by Netting (1993) and Schultz (1964), smallholders, while poor, are not only relatively more productive and efficient but rational in their decision making. The evolution of farming systems, the methods of maintaining and enhancing soil fertility, the level of technology in use and the labour input per unit land are all endogenous factors that are largely influenced by the agroecological and socioeconomic conditions with which smallholder farmers are confronted (Binswanger-Mkhize & Savastano, 2017). It is on this basis that Hayami and Ruttan (1985) justify the rationality of smallholders who persist with traditional crop varieties that do not respond to higher levels of fertilizer in countries with high fertilizer prices and/or low agricultural produce prices. These same smallholders, acting rationally again, would start to cultivate crop varieties responsive to higher levels of fertilization and will fertilize more in a context where prices of fertilizers are low and those of agricultural produce are relatively high.

Additionally, the Boserupian theory of agricultural intensification and the IIT have some similar core tenets, even if at different abstraction scales. For example, while in the former, population growth, at least in theory, leads to changes in the patterns of agricultural land use and tools employed, Kikuchi and Hayami (1980) demonstrate, using empirical data, how these changes actually ensue. In agreement with Hayami and Ruttan (1985), Turner and Fischer-Kowalski (2010), in expanding on the ideas of Boserup, theorize that farmers would shift to investing in new technical and other forms of innovations only if land and labour dynamics – resource endowments – pressure them to do so. However, their seeming similarity also implies that both the Boserupian theory of agricultural intensification and the induced innovation theory suffer from similar shortfalls. An example of this relates to the consequences of population growth on the ownership structure and availability of farmlands. Both postulate that private ownership emerges as agricultural lands become scarcer. The IIT deals with how scarcer and thus, more expensive farmlands would serve as a catalyst to induce farmers to intensify their cultivation and fertilize more. Boserup (1965) further holds that the level of land availability will differ for different cultivator categories. That is, where farmlands become scarce for shifting cultivators, farmers undertaking intensive cultivation may still appear to have abundance of farmlands. Using the SLA, however, brings to the fore how farmers in the same villages and using the same cultivation system could still have differing levels of access to farmlands based on their asset portfolios.

Furthermore, both the Boserupian theory and the IIT are explicit on the relationship between industrialization and agricultural development. The Boserupian theory draws a direct link between the two processes by positing that as long as a community or country is at a low stage of industrialization, only insignificant quantities of industrial inputs, such as fertilizers, are likely to be used in agriculture (Boserup, 1965, p. 91). The IIT goes further to explain that increased levels of industrial input use eases the constraints imposed by the largely inelastic supply of primary factors of production such as land and labour (Hayami & Ruttan, 1985, p. 129). Another way that the Boserupian theory and the IIT complement each other is that while the former explains how population pressure leads to shortening of fallow periods and hence the need to higher levels of fertilization, the former explains why, under certain conditions, it is still rational for smallholders to persist with limited levels of fertilizer use; namely low responsiveness of traditional crop varieties to higher levels of fertilizer use. Similarly, while the crux of the SLA is to explain how livelihood outcomes are constructed using the various forms of capitals, the IIT which categorizes these capitals into resource and cultural endowments, shows how technical change in agriculture is brought about through processes of mutual reinforcement. The Chayanovian model similarly complements the

SLA in that both are concerned with understanding the smallholder economy and of how the smallholders make a living given the specific constraints and opportunities that confront them on a daily basis. However, while the Chayanovian model is more abstract and less micro in terms of focus on the smallholder household, the SLA is more practical and more local in its approach to analysing the smallholder economy.

3.7 Localizing to the SSA context

From the foregoing, SSA agriculture would appear, from the outside and based on the annual statistics available on yield levels, as unproductive and should give way to more modernized, capitalist-oriented enterprises which would produce at levels required to sustain the growing population. Approaching the SSA agrarian question from this perspective fails to consider the peculiar milieu within which smallholders operate, their unique roles in the national economies or countries, and the challenges they contend with daily. As **Figure 3.3** shows, not only are smallholders in SSA confronted with underdeveloped and imperfect markets for both agricultural inputs and farm produce but they are also expected to meet their consumption needs in the face of high and continuously increasing population. Thus, the *ab initio* condition is one of underdeveloped agricultural input and output markets in the face of growing population and continuously increasing population density. Given this backdrop, subsistence farming becomes the most rational option with the smallholder household as the basic production and consumption unit. This gives rise certain limited responses that are available to smallholder households.

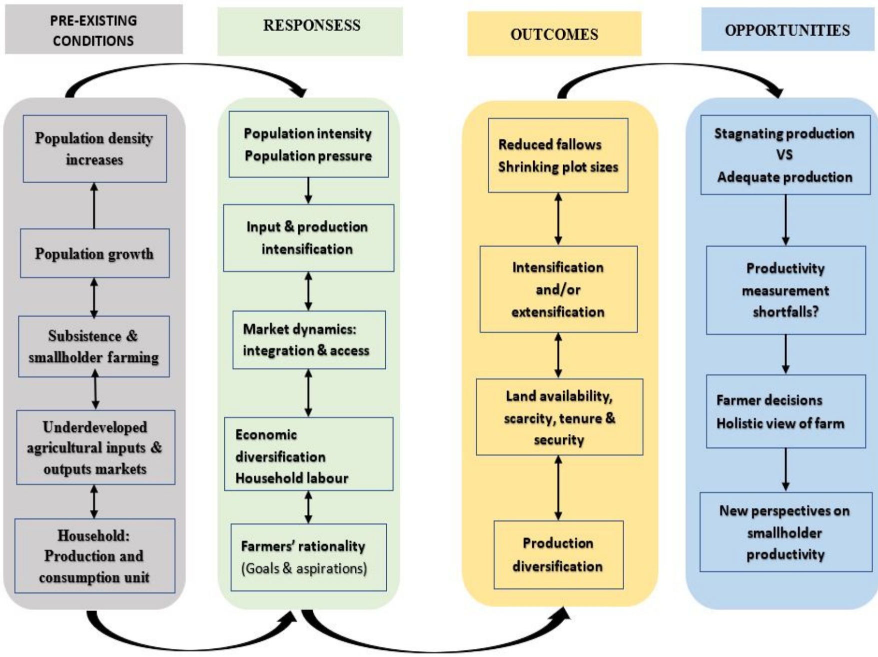

Figure 3. 3: A framework for new perspectives on SSA agricultural growth and dynamics: existing conditions, responses, outcomes, and prospects
Source: Author's construct

In terms of *responses*, current driving forces of population pressure, changing market dynamics in terms of prices, access, and integration in the face of smallholder rationality in terms of their goals and aspirations have important implications for input and production intensification as well as diversification. While the intensification may not presently be yielding the expected results, diversification – both on-farm and off-farm – appears to be producing some interesting outcomes. Reducing fallows and increasing fragmentation of farmlands, in addition to the market dynamics and technologies to reduce drudgery are contributing substantially to the intensification drive. These are rooted in the tenure systems in place in these contexts. Limitations relating to levels of fertilization to maintain soil fertility levels *vis-à-vis* increased cultivation intensity is resulting in increasingly less fertile soils. While these *outcomes* may appear negative, there are some *opportunities* inherent in them in terms of changing perspective on smallholder productivity in SSA.

In all of these, it is crucial to develop new perspectives that adequately cater to the peculiar context of smallholders in SSA in terms of their productivity. Doing this would require a review of some of the conventional methods for estimating yields. It is also important to take a closer look at the prevailing tenure systems, the security they engender and how these impact smallholder decisions, especially regarding farm investments. This would go a long way to dealing with some of the most challenging issues confronting SSA agriculture, namely: transforming largely traditional agrarian societies to overcome misery through the modernization of farming tools, techniques and methods in order to reduce drudgery; and then to upscale this process to transform national economies. Such transformations would include tools and technologies already in use in other regions of the world as well as newer ones that are now becoming possible through breakthroughs in computerization and miniaturization.

4 Materials and methods

> "When two or more people discuss the meaning of photographs, they try to figure out something together. This is, I believe, an ideal model of research". Douglas Harper, 2002, p.23.

4.1 Introduction

This chapter describes in detail the methods and techniques I used in collecting the data for the present study. However, first, I provide a brief description of the study setting. This is to provide context for the ensuing sections. The description is in two levels; at the country level and then narrowed down to the districts in which the study was carried out. The country overview discusses the Ghanaian economy with a focus on the agricultural sector and its contribution to the larger national economy. It also presents a brief description of the agro-ecological zones in the country. The description of the study districts with a specific focus on the study communities entails their location in space, the climatic conditions, levels of rurality and their agricultural dynamism.

Having done this, the next task is to describe the research design and methods. While the former provides a framework or structure that guides the collection and analysis of data, the latter entails the techniques or instruments for collecting data. Here, the research design and the multiplicity of methods and data sources used are discussed. The cross-sectional comparative case study using a mixed sequential explanatory research design is described in this section. Quantitative methods such as sampling of households and plots, household surveys, in-field measurements, and remote sensing of crops using a UAV as well as qualitative methods involving the purposive selection of informants, in-depth interviews, and field observation dairies are described in detail. Given the multiplicity of sources data sources and tools, questions of validity and reliability are then addressed. The limitations and delimitations of the study will also be discussed.

4.2 Providing context for the study

With a current population of about 28 million and a total land area of 239 thousand square kilometres, Ghana has a population density of about 117 persons per square kilometre (Kaneda & Bietsch, 2015; SRID-MoFA, 2013). Agriculture has been, and continues to be, one of three key sectors of the Ghanaian economy: the other two being the industrial and the services sectors. An important phenomenon that is increasingly having important implications for the agricultural sector in Ghana is the rapid rate of urbanization. The proportion of the national population living in urban areas has been increasing steadily from 9.4% in 1931, to 23.1% in 1960, 32% in 1984, 43.8% in 2000 and 51% in 2010; given that the country has crossed the rural-urban divide in about 2008 (Kaneda & Bietsch, 2015; Owusu, 2010). In spite of the rapid rate of urbanization, the rural population in absolute numbers has been on a consistent rise. Despite the high rate of rural-urban migration and the reclassification of many settlements as urban over the period, the population of people living in rural areas increased from 5 million in 1960 to 6 million in 1970, 8.4 million in 1984, 10.5 million in 2000 and 11.9 million as at the time of the last census in 2010 (GSS, 2014a; Songsore, 2009)[20]. These trends of increasing urbanization but growing rural population have important implications for the agricultural sector. Agriculture remains a key sector of the Ghanaian economy; accounting for 23% of the national GDP in 2012 (FAO, 2015b; SRID-MoFA, 2013).

Although it has recently been overtaken by the services sector in terms of contribution to national GDP, agriculture is still the largest employer – employing more than half of the active labour force. This is hardly surprising given that agriculture is still predominantly traditional – the cutlass and hoe being the main farming implements – and undertaken, largely, on a smallholder basis; as much as 90% of farm holdings are less than 2 hectares in size, notwithstanding the existence of some large farms and plantations, particularly for cocoa, rubber, and oil palm and, to a lesser extent, rice, maize, and pineapples (GLSS-6, 2014; SRID-MoFA, 2013). Intercropping is also a common feature, particularly on smallholdings with mono-cropping being more characteristic of larger-scale farms than on their smallholder counterparts.

[20] The present year, 2020, is a census year and the number of rural dwellers is expected to rise further. Given the increasing rural-urban migration, the rising rural population suggests that even larger numbers are being added to the rural population every year.

Despite its importance as an employer in a middle-income country, the growth of the agricultural sector, just like that of the larger national economy, has been erratic, particularly in the last decade. To illustrate, after recovering from a low of -1.7% in 2007 to grow at above 7% for 2008 and 2009, it declined significantly again to 0.8% in 2011 before somewhat recovering to about 5% in 2013 and 2014, only for it to plummet to its lowest levels of 0.04%, with the crops sub-sector growing at negative values for 2015 (GoG-FAO, 2013; MaED-MoFA, 2014; MoF, 2017). This unpredictability of the growth rate of the agriculture sector is symptomatic of the challenges confronting the agricultural sector of the country. While soil factors are important, agricultural production also varies with the amount and distribution of rainfall given the limited level of irrigation activities; just about 5% of the cultivated area was under irrigation in 2012 (SRID-MoFA, 2013).

Ghana has six main agro-ecological zones: The Rain Forest, the Deciduous Forest, the Transitional, the Coastal Savanna, and the Guinea and the Sudan Savanna Zones; defined on the basis of climate and reflected in the predominant natural vegetation and length of the growing season. The Rain Forest, the Deciduous Forest, and the Transitional zones are often termed the breadbasket of the country. Administratively, Ghana is now divided into 16 regions[21], with the selected study region – the Eastern Region – located in the middle belt of the country and in the Semi-Deciduous Forest agro-ecological zone.

By selecting the Eastern Region for this study, the extremely wet and most agriculturally-endowed regions – Western, Ashanti and Brong-Ahafo and Bono East Regions, which all fall within the Tropical Rainforest zone, as well as the driest – Northern, Upper East, North East, Savannah, and Upper West Regions which all fall within the Savanna zones, are all disregarded. At just 51%, the technical efficiency of maize farmers in the Eastern Region is the lowest (Kuwornu & Wayo, 2013) compared to 58% in the Central Region (Essilfie, Asiamah, & Nimoh, 2011); 67% in the Ashanti Region (Bempomaa & Acquah, 2014); 74% in the Northern Region (Abdulai, Nkegbe, & Donkoh, 2018) and; 91% for maize farmers in the Brong-Ahafo Region (Sienso, Asuming-Brempong, & Amegashie, 2014). The choice of the Eastern Region and the study villages was, thus, with a view to capturing the dynamism of agricultural production systems in Ghana and study the prevailing *above average* regions in terms of their ecological and market endowments and thus

[21] The country until 2019 had 10 regions but it was re-demarcated into 16 regions, and further divided into 216 administrative districts. The Eastern Region was, however, not affected by the regional reorganization.

excludes the most extreme cases at both ends of the *agricultural dynamism/potential spectrum* (G. Djurfeldt, Holmen, Jirström, & Larson, 2005). The aim was, therefore, to arrive at villages that illustrate the prevalent conditions in typical maize production regions of the country while excluding outliers at both extremes; very dry, remote, and low-potential areas and very wet, privileged high-potential areas (G. Djurfeldt, Aryeetey, & Isinika, 2011). These factors led to the selection of the Lower Manya Krobo Municipality and the Upper Manya Krobo Districts of the Eastern Region and subsequently the selection of Asity and Akatawia, respectively, as study villages.

4.2.1 The Lower Manya Krobo Municipality: Asitey

Asitey (Lat. 6.129601°, Long. -0.013253°) is less than 1km from Odumase, the municipal capital of the Lower Manya Krobo Municipality of the Eastern Region of Ghana (Figure 4.1). The municipality covers an area of 304.4sq.km and with a total population of 89,246 (84% urban and 16% rural), it has a population density of 293 persons per square kilometre. In terms of climate, the municipality lies within the Semi-Equatorial climate belt of West Africa with mean annual rainfall ranging between 900mm and 1150mm, and average temperatures ranging between 26°C and 35°C. Its location also ensures that it experiences two major seasons: the rainy season and the dry (Harmattan) season, with the rainy season being the double-maxima type. The major rainy season is experienced between April and early August while the minor one occurs between September and early November. The municipality is relatively flat with isolated hills. The undulating landscape is well-drained by a number of water bodies, most of which empty into the Volta Lake, which covers large sections of the Eastern boundaries of the municipality. Thus, notwithstanding the high population density leading to fragmented farmlands, agriculture is an important economic activity, with 33% of the households in the municipality and 66% of rural households engaged in it. Like most of the country, maize is the most important food crop (GSS, 2014b). The major market centres in the municipality are Somanya, Odumase, and Kpong, with the municipality being directly connected to the major metropolitan centres of Accra and Tema.

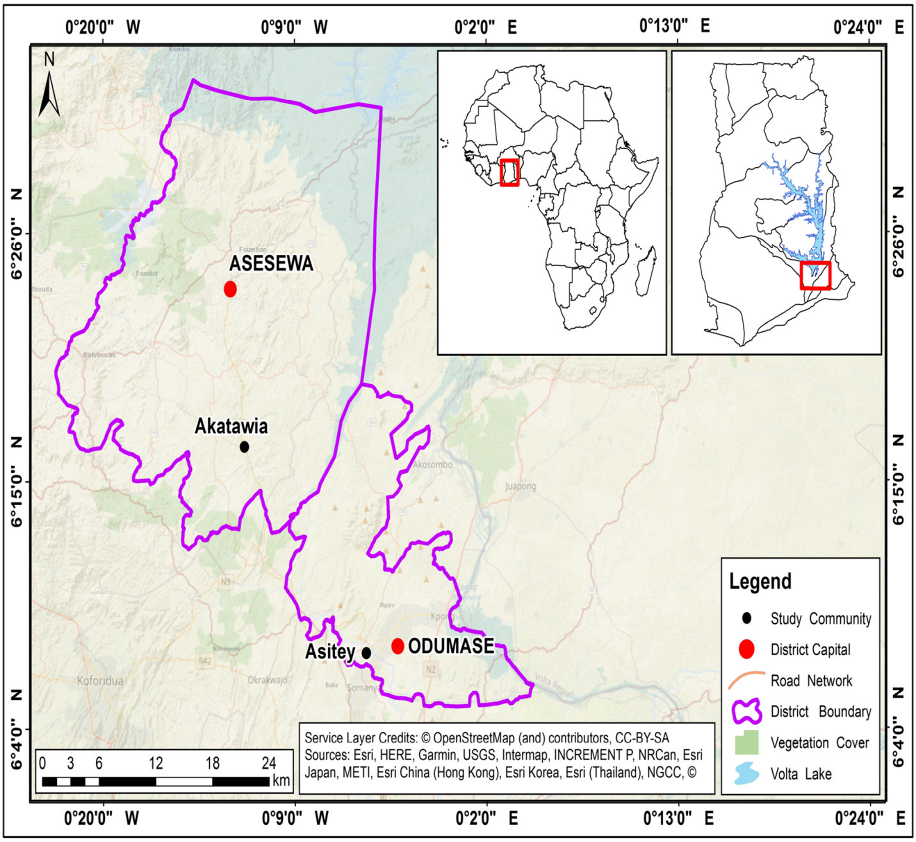

Figure 4. 1: Map of the study districts showing the locations of Asitey and Akatawia villages
Source: Author's construct using OpenStreetMap

4.2.2 The Upper Manya Krobo District: Akatawia

Akatawia (Lat. 6.283055, Long. -0.128794) is about 9km from Asesewa, the capital of the Upper Manya Krobo District of the Eastern Region of Ghana. The Upper Manya Krobo District has a total population of 72,092 (87% rural and 13% urban) with a total land area of 859 square kilometres; giving it a population density of 84 persons per square kilometre. Thus, the district is largely rural in character with less population pressure, compared to the Lower Manya Krobo Municipality. In terms of vegetation, the district falls within the Semi-Deciduous Forest and Savanna. It experiences a Semi-Equatorial climate, with mean annual rainfall ranging from 900mm to 1500mm with similar temperatures and cropping seasons as the Lower Manya Krobo. The district is also very well drained since the Volta Lake borders most of its North-Eastern boundaries. Given these conditions, agriculture is unsurprisingly a major economic activity, with as much as 73% of the population employed in that sector and maize being the main food crop cultivated. The district is also served by three main market centres at Akatim, Sekesua and the famous Asesewa markets with markets days operating interchangeably among these centres on a 5-days-per-week basis (GSS, 2014c).

4.3 Research design

This study uses a cross-sectional comparative case study using a mixed sequential explanatory research design as shown in **Figure 4.2** below. A cross-sectional research design entails the collection of data on *a sample of cases* and at *a single point in time* in order to collect a body of quantifiable data in connection with two or more variables, which are then examined to detect *patterns of association* (Bryman, 2016). Comparative design entails studying two contrasting cases – in this case, Asitey and Akatawia – using identical methods in order to understand social phenomena better. A case study entails the study of a single instance or a small number of instances of a phenomenon in order to explore in-depth nuances of the phenomenon and the contextual influences on and explanations for that phenomenon (Baxter, 2010). The case study design thus lends itself to the employment of both qualitative and quantitative research (Bryman, 2016). With the primary guiding philosophical assumption that in-depth understanding about the manifestation of a phenomenon or case is valuable on its own, case studies play two key but not necessarily mutually exclusive roles: to test theory and to generate or expand theory (Baxter, 2010). Thus, practical reasons – including financial and time limitations – as well as academic considerations, informed the choice of a cross-sectional comparative case study design.

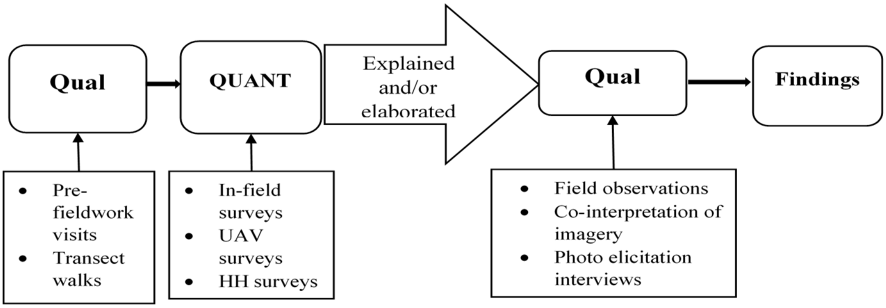

Figure 4. 2: A mixed sequential explanatory research design
Based on Bryman (2016, p. 639).

The study thus employs mixed methods in a sequential but integrated approach (qual-quant-qual) as shown in **Figure 4.2**. P. Davis and Baulch (2010) argue that such a sequential but integrated approach gives certain advantages over single method approaches or non-integrated studies including strengthening our ability to make more reliable causal inferences and linkages. Further, Teye (2012) avers that while the quantitative approach entails the use of statistical techniques for analyzing quantifiable data and is thus useful for establishing the nature of correlations between different variables, qualitative instruments are most effective for generating data on experiences, perceptions, and behaviours of research participants (p. 380). As Winchester and Rofe (2016) posit, contemporary human geographers require a multiplicity of conceptual approaches and methods of inquiry in order to sufficiently answer the research questions that they are confronted with.

The first qualitative part entailed pre-fieldwork activities of 'casing the joint' during which period discussions were held with the chief farmers, assemblymen and women and other key stakeholders of both communities. Transect walks were also done on selected plots to gain first-hand knowledge of prevalent farm management practices in the communities. These initial discussions provided important information concerning agricultural activities including the farming calendar of the communities as well as other information that would be useful for the design of the survey instrument for the next stage of the study. The quantitative leg coincided with the major maize planting season and entailed plot surveys, household surveys, and agronomic measurements on farm plots.

Initial analysis of the quantitative data then led to the second qualitative part, which entailed structured observations and in-depth photo-elicitation interviews. The latter was carried out for farmers with different production capabilities for each study location. As Banerjee et al. (2014) point out, farmers are not a monolithic group; they contend with different constraints in their farming decisions based on the resources available to them. The authors posit that such categorizations reflect differences in potential access of various households to resources for managing their crops and are often constructed based on information emanating from surveys, key informant interviews, focus group discussions, and literature on biophysical and socioeconomic characteristics of the farmers.

Furthermore, combining and integrating both qualitative and quantitative approaches in this study affords the study other advantages. First, where quantitative tools such as surveys tend to be rigid in the way responses are elicited from respondents, qualitative instruments such as interviews are more flexible in this regard, allowing the researcher to follow interesting leads in the course of data collection. This is in line with the interpretive paradigm, which assumes that social reality is multifaceted and that the primary aim of social research is to elucidate the subjective behaviours of people (Bryman, 2016). Second, the relatively limited number of farming households – 30 from each community and 60 in total – means that one cannot claim the quantitative sample is representative of the two communities. Thus, the fusion of methods is not only desirable but essential in order to provide depth for the study. Third, a fusion of methods allows triangulation of data through cross-checking as a basis for validating answers and conclusions reached in the study (Creswell, 2009). For instance, in surveys, respondents have been known to be quite apprehensive in answering questions on income sources and amounts but an in-depth interview with a research participant is well-suited for teasing out certain useful details concerning secondary income sources among others. Thus, this fused approach provided a more nuanced understanding of the underlying socioeconomic constraints of crop yields in the study communities by sufficiently assessing, describing and analysing performance at the farm level. In a nutshell, while the quantitative aspects of the study helped unravel the relationship between certain social and economic variables and crop yield levels of individual farming households, the qualitative tools are invaluable in understanding the reasoning underlying these observed patterns as well as smallholders' perceptions of risks and the constraints that confront them.

4.4 Quantitative data collection

The crux of the quantitative approach is steeped in the positivist paradigm and seeks to discover general patterns of behaviour and entails the use of statistical techniques for analysing quantifiable data (Teye, 2012). The quantitative data for the study was collected using household and plot surveys, as well as through UAV flights. The quantitative methods enabled the collection of quantifiable data such as crop output, plot area, and other measurable data in order to derive yields and draw linkages with variables.

4.4.1 Sampling of households and plots

A multi-level sampling strategy was employed for this study. The eventual sample for this study was the same sample used by the AFRINT survey (G. Djurfeldt et al., 2005). Essentially, there were four stages of the sampling process: country, region, village, and household levels. All stages, apart from household sampling, were purposively selected. Given the quantum of the multidisciplinary data that was collected per household and plot *vis-à-vis* the time within which maize crops grow per season, a relatively small sample size of 30 households per village was decided on with a list of all maize farmers in each village as the sampling frame. Once the sample frame was at hand and the desired sample size had been decided, a *simple random sampling method* was used to arrive at the 30 households for each village. Given that this list was originally developed years ago, it was expected that some of the respondents would have passed, out-migrated or were no more engaged in maize cultivation due to old age and/or ill-health. Where this applied, the next of kin, closest relative or another member of that household was drafted to replace the absent respondent. The AFRINT project, thus, used only to help identify the maize farm households in the study villages.

In selecting plots, a few of the households had multiple maize plots at different locations. Others had a single maize plot, but in order to be able to quantify how such variables as fertilizer application and management, among others, related to yields, there needed to be sufficient homogeneity on sampled plots. This implied that even in situations where a plot operator considered a plot as a single unit but I discerned notable heterogeneity emanating from differences in slope, plot history and planting time, such a large plot was disaggregated into smaller, more homogeneous plots. It is on these basis that, in some circumstances, plots 1 and 2 of the same household could lie adjacent to each other and yet be treated as separate plots. Thus, with the total household number of 60, there were 87 plots, giving an average of 1.45 plots per household. A 4m by 4m sub-plot was demarcated at the centre of each plot within which all the agronomic measurements were carried out. To avoid any bias such as selecting portions where crops look healthiest or poorest compared to the larger plot, the sub-plot was demarcated before planting. Where the centre of the plot is incumbered by an obstacle and this was not representative of the larger plot, the subplot is moved 5m north from the actual centre of the plot. Such obstacles could be a footpath, a termite mound, a large tree, or a location where large quantities of biomass had been heaped and burnt.

The household surveys covered 60 households: 30 from each village. Basic household data such as geographic location, age, gender and educational attainment of household head, household size and structure were collected. Other important data collected during the household surveys includes the household's total landholding and usage, secondary/non-farm income sources, proportion of farm/non-farm income and household income bracket, agricultural information sources and availability, and market accessibility, among others. The main respondents for the household survey are household heads.

4.4.2 In-field surveys

Sampled households had between one and three maize plots. Where a household had more than one plot, it is interesting to note that usually, the male head had direct responsibility for only one of the plots, with the others being directly managed by other household members. In total, there were 87 plots between the two study villages. Data collected during the plot surveys included plot history and cropping patterns, land preparation methods, labour use, crop planting data, intercrop data, fertilizer (organic and inorganic fertilizers) use, weed control (frequency and methods), irrigation, use of previous season's crop residue, reliance on credit facilities, and crop harvest data, among others. The respondents for the plot surveys were usually the plot operators. Thus, respondents of both surveys are not necessarily the same for a given household. Apart from the plot surveys, other plot-specific data were collected through transect walks of the plots. Three rounds of field measurements were conducted at various stages of the crop growth cycle: at approximately 5 weeks after planting, 10 weeks after planting, and 14 weeks after planting. Data collected during the field measurements include plot coordinates, plot sizes, slope and erosion status, penetrometer and SPAD meter readings, crop development stage, height, vigour and density, weed coverage, among others.

4.4.3 Remote sensing surveys

The Unmanned Aerial Vehicle (UAV) used for remote sensing of the farms was equipped with a vertical takeoff and land (VTOL) system and so did not require a runway for takeoff and landing. This is in contrast with the catapult-launched systems, which need a relatively flat and unencumbered terrain for landing. Given the impracticality of this in the study communities, the VTOL-equipped UAV was most appropriate for our purposes. The UAV system comprised an Enduro quadcopter (Agribotix, CO, USA) powered by the Pixhawk flight control system (3D Robotics, CA, USA) and mounted with two GoPro Hero 4 cameras (GoPro Inc., San Mateo, CA, USA). The two cameras are identical except one is modified to capture in the near infra-red (NIR) region of the electromagnetic spectrum. The unmodified lens captures images in red, green, and blue (RGB). The red band in the modified lens is covered with a special filter in order to capture reflectance in the otherwise non-visible NIR region (Agribotix, 2018; Underhill, 2018). This is done by replacing the 5.4 mm ½. 3´´ IR CUT MP-10 lens with a 5.4 mm ½. 3´´ IR MP-10 lens and thus enable the green NDVI for crop health mapping (Agribotix, 2013; Underhill, 2018). Both the modified and the unmodified cameras capture images autonomously and simultaneously and so can complement each other when need be (Mesas-Carrascosa et al., 2015).

The camera gimbal, which provides a platform and stability for the cameras to forestall blurring in images, is affixed to the quad frame and tilted at 10° to the ground and set to shutter every one second. The aerial system is supported by on-ground gear including the Ground Control Station (GCS) – a Windows PC installed with Mission Planner programmes for planning the flight paths of the UAV system. On the ground is a radio system, which enables the telemetry link between the UAV while in flight and the GCS, as well as a remote-control transmitter (FrSky Electronic Company, Wuxi, Jiangsu, China) used for controlling the UAV system during take-off and landing.

On a full battery charge, the Enduro system can cover an area of ~65 hectares per flight. However, due to the relatively small sizes of maize plots in the study area and dispersed rather than clustered nature of the farm plots, flight durations ranged between 5-15 minutes. As a safety precaution, the system has also been equipped with the 'return to home' feature so that in case of emergencies such as prolonged loss of telemetry link or batteries dropping below 20%, the UAV system will independently return to the takeoff position. During field missions, the UAV system is flown autonomously at an altitude of ~100 meters above sea level in a survey grid format at a speed of 14 m/s with 80% lateral overlap and 60% longitudinal overlap. The ~100-meter flight altitude is not only recommended by law but is also ideal as it is sufficiently above some of the tallest trees and yet low enough to capture, in adequate detail, the crop canopy. The UAV thus fills the gap between manned aircraft and in-field crop measurements.

4.5 Qualitative data collection

While quantitative methods are ideal for quantification and assessment, qualitative methods are well-suited for digging deeper. The qualitative approach is underpinned by an interpretivist epistemology and rooted in the constructivist ontology; emphasizing the presence of 'multiple truths' that are socially constructed and, thus, can be uncovered through an inductive approach. Qualitative research methods are intended to elucidate human environments, individual experiences, behaviours, and perceptions, as well as social processes and structures (Teye, 2012; Winchester & Rofe, 2016). That is, qualitative tools such as in-depth interviews, structured observations, and co-interpretation of imagery are most suited for understanding marginalized groups such as poor smallholder farmers and their experiences of the phenomenon under investigation. In this regard, Dunn (2010) avers that when a method is required to fill a gap in knowledge that other quantitative tools are unable to bridge efficaciously, to collect a diversity of meanings, opinions, and experiences, or to empower informants and place value on their viewpoint, then the qualitative method of interviewing is the method of choice. It thus enables silenced voices to be heard and fosters a better comprehension of those mainstream discourses that exclude and marginalize certain social groups. With its emphasis on the meanings people ascribe to phenomena around them, qualitative methods are suitable for revealing the thoughts and perceptions of individuals of societal structures and processes and how these inform their choices and attitudes. Herein lays the essence of the qualitative leg of the study. It entailed the use of field observation diaries as well as co-interpretation of UAV imagery in photo-elicitation interviews with farmers.

4.5.1 Purposive selection of informants

Unlike the quantitative approach in which the randomization of the sampling process is fundamental to ensuring representativeness of the sample and, by extension, the generalizability of the findings, the primary preoccupation of the qualitative approach is not a generalizability of findings (Hammersley & Atkinson, 2007). The underlying principle of the qualitative approach is the selection of the right people who possess relevant insights, characteristics, and experiences of the subject under study (Bradshaw & Stratford, 2010). Cloke et al. (2004) aver that choosing whom to interview involves the targeting of people who are likely to have the desired knowledge, experience, and positioning and who may be willing to divulge such knowledge to the researcher. Thus, the design of this study – with the quantitative leg carried out first – afforded me the opportunity to purposively select informants who meet certain desired characteristics and qualities for the qualitative segment. This is in sync with the view of Bryman (2016) that in mixed methods studies, findings from a survey may be used as the basis for the selection of informants.

In terms of the selection of informers for the qualitative leg of the study, the stratified purposive sampling approach was adopted (Bryman, 2016). This choice allowed us to select farmers at different levels of productivity. In terms of the sample size of informants, while Warren (2002) recommends a minimum range of 20 to 30 interviews for a qualitative study to be published, Adler and Adler (2012) propose a range of 12 to 60, with an average of 30. The differing views on the ideal size of informants arise from the fact that the suitable size for drawing reliable and valid conclusions depend, to a large extent, on specific circumstances and qualitative researchers have to be reflexive about this (Bryman, 2016). Overall, it is crucial to be guided by Onwuegbuzie and Collins (2007, p. 289) admonition that: *"sample sizes in qualitative research should not be so small as to make it difficult to achieve data saturation…At the same time, the sample should not be so large that it is difficult to undertake a deep, case-oriented analysis"*.

Table 4. 1: Distribution of qualitative research participants

Study village	Below average performers	Average performers	Above average performers	Expert interviews	Total
Asitey	4	4	4	1	13
Akatawia	4	4	4	1	13
Total	8	8	8	2	26

Source: Author's construction based on field data, February 2019.

To this end, 12 key informants were purposively selected for the in-depth interviews for each study community. The breakdown was as follows; four high performing smallholder maize farmers, four whose plots were poorly performing and four whose plots were performing averagely. Additionally, two experts – one from each study community – were interviewed for their in-depth knowledge, diverse experiences, and unique perspectives relative to the subject matter of the study. The experts for each community were the District Agriculture Officers (DAOs) and the Chief Farmers for each study community. Thus, in total, 28 interviews were conducted, and the particulars are given in **Table 4.1**. Furthermore, all household heads whose plots have been flown were engaged in the co-interpretation of the UAV imagery. This is based on the fundamental principle underlying the qualitative approach that premium ought to be placed on the *informants' views of the facts* and that seeing through the eyes of the research participants is more important than documentary sources or the researcher's view of what is true (Bryman, 2016).

4.5.2 Field observation

This method of data collection was key during the field surveys. It involved taking visual stock of the farm fields and homes of smallholder farmers to gain insights into their socioeconomic milieus and the farm management practices that were otherwise not captured in the field and household surveys. This kind of observation is distinguishable from the more active participant observation, which involves a certain degree of participation in the activity of the research by the researcher (Hesselberg, 2013). Throughout the six (6) month duration of the fieldwork, I kept a field observation diary in which field observations, reflections, and additional data emanating from informal conversations with farmers while they prepared their plots were recorded. Generally, notes were quickly written down after observing or hearing phenomena that pique my attention. More detailed notes were then written at the end of each day, which included details such as who is involved, date and time as well as researcher's own personal reflections of the observation.

The field observation dairy became a source of rich data throughout the writing stages of this work. I found, for instance, that key snippets of information would have escaped from memory if they were not immediately recorded while in the field. While there is often the temptation in contemporary times to use a digital recorder instead, there are some shortfalls of the latter that needs to be considered. In addition to further burdening the researcher with the need to transcribe a lot of speech (Bryman, 2016), the realization of being recorded has the tendency to induce hesitance on the part of informants. This is contrasted with the interview situation whereby the interviewee is pre-informed of being recorded as part of seeking informed consent.

4.5.3 Photo elicitation interviews (PEIs)

Interviews are most effective at gaining access to information about events, opinions, and experiences; the latter two may vary substantially between people of different class, income, ethnicity, age, and gender (Dunn, 2010). Interviews are particularly proficient at revealing the underlying story of a participant's experiences, pursue in-depth information about a phenomenon as well as gain insights from earlier responses from a survey. By their very nature, interviews provide 'thick descriptions' (Geertz, 1973) about informants' attitudes, preferences, behaviours and knowledge; and thus help to better understand and explain the 'why' and 'how' of the presence or absence of phenomena. Placed on a continuum, there are three major forms of interviewing with the structured interview on one end of the scale and the unstructured on the other end of the continuum. This study employs the kind in the middle of this scale, the semi-structured interview. This type of interviewing uses a question guide but affords the researcher a certain degree of flexibility in the way issues are addressed by the informant (Dunn, 2010). This flexibility enables the researcher to pursue interesting leads during interviews while the question guide provides direction for the interview.

The use of photographs is a further way in which questioning in qualitative interviews may be grounded. Also termed *photo-elicitation*, the use of photographs during interviews serve a number of useful roles; grounding the researcher's interview questions, stimulating interviewees to engage visually with settings, and interviewees to remember people, events, and situations that they might have forgotten (Bryman, 2016). Harper (2002) documents how the use of less familiar visual research methods such as aerial photographs stimulated farmers to engage in more thinking during interviews and posits that "images evoke deeper elements of human consciousness than do words" (p. 13). Thus, the synoptic view of UAV photographs of farm plots gave farmers a peculiar view of their farms from a vantage point. This served to engender more interesting data from the interviews. In all, there were 82 plots with aerial photographs for both study communities. The aerial photographs were most useful in eliciting insightful responses from their respective managers.

With renewed enthusiasm for the use of visual methods in qualitative research (Barbour, 2014), photo elicitation interviewing (PEI) is based on a fairly simple principle of using one or more images in an interview and asking the informants to comment on them (Bignante, 2010). PEIs complement conventional interviewing by facilitating communication, improving rapport building and eliciting tacit knowledge (Pain, 2012). By so doing, PEIs enhance the richness of the data by discovering additional layers of meaning by stimulating informants' ability to express their practical knowledge through attribution and association of meaning (Bignante, 2010; Glaw, Inder, Kable, & Hazelton, 2017). The strength of PEI, as a data collection method, lays in the fact that images evoke deeper elements of human consciousness than words do (Harper, 2002). It thus bridges the geographical, communication, and cultural lacuna that could exist between researcher and informant (Bignante, 2010). The utility of PEIs is therefore encapsulated by the quotation at the beginning of this chapter on the powerfulness of co-interpretation of images in research.

In total, there were 24 photo-elicitation interviews with smallholder maize farmers – 12 from each study community. Each of the 24 interviews lasted between 30 and 45 minutes. The 12 interviews in each study community comprised 4 with farmers whose plots performed averagely in terms of yields, 4 with outstanding performers and the final 4 with farmers whose plots performed the worst in terms of yields. This approach is to ensure that data is collected from farmers who fall across the whole spectrum of productivity. There were repeat interviews with 6 of the farmers who seemed to have additional information and were keen to divulge such insights. These were done until further interviews yielded no new information.

4.6 Ethical and positionality considerations

Ethical considerations in the social research process are crucial and essentially concern the conduct of researchers and their obligations and responsibilities to those involved in the research, particularly the research participants (Bryman, 2016). Social research in general and qualitative research techniques, in particular, necessarily occur in uncontrolled societal contexts. The onus, therefore, rests on the researcher to ensure that informants are adequately protected. It is pertinent to note, however, that the ethical issues that come to the fore in any research are contingent on the research technique in use. Thus, ethical issues that need addressing in a study on HIV-AIDS survivors would be quite different from that on the psychological effects on childhood molestation on adults or that on the poor yields of smallholder farmers. In the present study, issues on disclosure and informed consent, anonymity and confidentiality, and dissemination and feedback to participants are discussed. My positionality with regards to research participants, issues on power and insider/outsider relations also came to the fore.

Disclosure and informed consent entail the comprehensive briefing of informants on the nature and purpose of the study, and the right of informants not to participate or withdraw the consent already given (Bhattacherjee, 2012).

Even before engaging individual smallholder farmers, permission was sought from the farmers' chief and the Assembly Person for respective study communities. Such gatekeepers exert substantial influence among farming households and are important influencers. Their support bodes well for not only the present but also future research endeavours. Securing informed consent was not too problematic given that most of the sampled smallholder farmers for the present study had been involved in related previous panel study going back more than a decade. This notwithstanding, full disclosure and informed consent was secured by explaining in detail the nature and scope of the study, what was expected of them as research participants, and the fact that they could refuse to answer particular questions or indeed completely opt out of the study at any point in time. Disclosures on the purpose of the study, the outcomes expected, and who would benefit from the results was often tricky. The latter, for instance, often elicited the question of 'what is in it for me?' from participants. While the underlying motive for such a question is usually monetary compensation, this has ethical considerations. On a number of occasions, I responded to this query by explaining the benefits of the knowledge that would result from the study to the larger community through a feedback workshop[22] that would be organized to disseminate the findings from the study. Improved seeds were also distributed to research participants at the end of the study although they were not informed beforehand of this possibility since this could have biased their responses in the surveys.

The use of pictures has always had some conundrums that need addressing (Holm, 2014). Ethical issues are even more important in photo-elicitation interviews. While farmers were fascinated by the gNDVI images of their plots, which depict the crop vigour from an aerial perspective, a few of the farmers sought to look at those of their neighbouring colleagues for the purposes of comparison. While this might appear harmless, it could be tantamount to sharing data collected from one research participant with another, which would be unethical. I, therefore, dissuaded farmers who asked to see other farmers' UAV images with the explanation that it was unacceptable, and they might not like to share their own results with others. Each farmer was thus supplied with the imagery of only their own plot.

Anonymising the data collected with a view to protecting the privacy and confidentiality was also crucial. Anonymity implies that readers of the final

[22] A feedback workshop was organized in November 2018, one in each village. During this workshop, general findings from the study were discussed and farmers concerns and views were sought. Finally, recommendations regarding soil management, including methods and timing of fertilizer application were proffered by soil experts from the large project.

report of the study or journal articles from the study cannot identify specific statements and responses with the particular respondent (Bhattacherjee, 2012). While not anticipating any potential harm that participants would suffer by virtue of having participated in the study, the use of pseudonyms ensures the anonymity and privacy of interviewees. With such methods as interviews, anonymity is practically impossible given that there are face-to-face interactions between the researcher and smallholder farmers over the course of the farming season. Thus, at the start of each interview session, the study participants were assured that any information they divulged would remain in my sole custody and that audio recordings would be kept in secure locations and would not be made accessible to third parties.

In line with assurances given to research participants at the beginning of the study, a dissemination and feedback workshop was organized after the initial analyses of the data collected. This workshop served a dual purpose: to disseminate the findings of the larger research group and member checking to ensure that our findings, by and large, correspond with their lived experiences. This proved a useful tool for crosschecking our findings. Given that the larger project from which this Ph.D. was carved out is a comparative study of farmers in Ghana and Kenya, it appeared initially that the Ghana yields were unusually low in comparison to both the Kenyan one as well as previous yield data from the same study communities in Ghana. The feedback workshop allowed the researcher to get confirmation for the present yield data and explanations for it. The 2016 major farming season was a particularly bad one with regards to the rainfall amounts and distribution, *vis-à-vis* the rainfed nature of the farming system being practiced in the study communities. Even more important, it was the first and most severely-hit season of the Fall Armyworm infestation that has been devastating maize farms in SSA over the past couple of years.

In terms of my position as an insider/outsider, this was quite dynamic. This is so given that the study took place over a three-year period from the major farming season of 2016, which started in March of that year to the qualitative interviews that were conducted in February 2019. Thus, even though I may have started out as an outsider, I eventually attained the status of an insider and gained enough confidence and trust of farmers for them to share more enriching and insightful information with me that they would not have done with an outsider. My ability to speak the same language with most of the informants was helpful. This, together with my regular contact with them in the course of three years convinced them that I was not 'just one of the researchers who come and collect data from them and vanish not to be heard from again'. This helped in no small way to establish rapport between the informants and myself during interviews. As Dowling (2010) explains, as an insider, both the information you create and the interpretations of it are likely to be more valid and reliable than those of an outsider. He further opines that people are more likely to talk to a researcher freely, and the researcher is more likely to understand what informants say because they share their world view, maintaining that establishing rapport is more difficult for outsiders than insiders. The merits and demerits of being an outsider or insider, of course, are relative and context dependent. This implies that, in situations where am convinced that adopting an outsider position would elicit deeper insight, I do so, with due recognition to ethical values.

With regards to the power relations, smallholder farmers could be described as wielding less power relative to other social groups. It was crucial, therefore, that I was reflexive and reflective of the potentially exploitative power relations between myself as researcher and farmers as research participants by being aware of, understanding, and responding appropriately to it (Dowling, 2010). This implied, for instance, deliberate actions and inactions on my part to not exert my influence even when informants were offering to accommodate those demands. While such actions do not eliminate the asymmetrical power relations, they seek to level the ground. This called for a reflection on how my positionality in relation to the processes, people, and phenomena under study affected those phenomena and my understanding of it. The photo elicitation interviews required that I visit their homes and posed prying questions regarding their productivity on their farm plots. This necessarily implied invasion of their private space and so there was the need, for instance, to regularly remind them that they had the right not to answer specific questions if they felt uncomfortable or completely withdraw their initially given consent.

4.7 Validity and reliability

Validity and reliability are a critical component of any research endeavour as they provide the basis to determine the objectivity and credibility of any piece of study. While issues bordering on validity and reliability may differ between qualitative and quantitative epistemologies, researchers from both schools ought to concern themselves with the reliability of their methods and the validity of their conclusions. As Silverman succinctly posits: *"Short of reliable methods and valid conclusions, research descends to a bedlam where the only battles that are won are by those who shout the loudest"* (2009, p. 274). Validity refers to the accuracy of data compared with acceptable criteria while reliability denotes the extent to which a method of data collection yields consistent and reproducible results when used in similar circumstances by different researchers or at different times (Hay, 2010). While the validity and reliability concerns of qualitative researchers may vary and take a less prominent role compared to that of quantitative researchers, as social scientific endeavours, both are concerned with the integrity and truthfulness of studies. Threats to validity could be minimized through a number of ways; ensuring internal and external validity, face validity, concurrent validity, convergent validity, construct validity and predictive validity while three considerations are key to ensure reliability: stability or test-retest reliability, internal reliability, and inter-rater reliability (Bryman, 2016; Creswell, 2009).

In this study, a number of strategies were employed to ensure validity and reliability. For the quantitative side of the study, *pre-tests* were conducted for each village for the preceding minor season on the plots of about 20% of the households that had been sampled for the main study. This was to ensure that there was consistency in the methods developed for the study and thus the test-retest method of attaining stability was used. However, specific plots that were used for the pre-tests during the minor farming season were excluded in the main study during the major season given that households commonly had multiple maize plots, often at different locations concurrently for each farming season. Face validity was achieved through validation of concepts from the supervisory team with more experience and expertise in the field. Furthermore, the use of the same researcher to undertake scoring based on the FAO guide on weed coverage and crop vigour based on a visual assessment (FAO, 2006) nullified the need to ensure inter-rater reliability; the inconsistency that may result from disparities in scoring between different raters in the same study.

In qualitative research, issues of validity and reliability are best addressed through *triangulation*. There are four main types of triangulation: data triangulation, investigator triangulation, method triangulation, and theory triangulation. The use of a multidisciplinary team of researchers from three countries (Ghana, Kenya, and Sweden) allowed for investigator triangulation and lends the present study a measure of validity through investigator triangulation. Furthermore, the triangulation of qualitative and quantitative methods proved to be important for the reliability of the study. Thus, the quantitative data obtained during the UAV surveys was validated through member checking during the photo-elicitation interviews in the qualitative leg of the study. This was done through farmers confirming that sections of their plots that depict less crop vigour based on the gNDVI images of their respective plots actually had less vigour and vice-versa. By so doing, method triangulation was also employed to ensure the validity of the index and the reliability of the conclusion drawn thereof.

On validity, of particular interest is the challenge with regards to the interpretation of photographs by informants based on their habitus and perspectives (Holm, 2014). Thus, both the researcher who produced the representation and the research informants necessarily add their social subjectivity to the interpretative process (Aitken & Craine, 2005). This notwithstanding, photo elicitation helps to collect more qualitatively and quantitatively complete data compared to that obtained from using only words (Bignante, 2010). As DiBiase, MacEachren, Krygier, and Reeves (1992, p. 202) argue "photographs and imagery, whose spatial dimensions correspond with those of the physical object being depicted, are more realistic than graphs, whose spatial dimensions represent nonspatial quantitative data or diagrams in which spatial relations are topological". Visual methods such as photo elicitation interviewing, thus, enhance the validity and depth of studies by adding to the richness of the data collected through the discovery of additional layers of meaning and by stimulating tacit knowledge (Barbour, 2014; Glaw et al., 2017; Pain, 2012). As Aitken and Craine (2005) further argue, such approaches must be concerned with systems of meaning; particularly with regards to how the landscape is viewed, experienced, and created by the people who populate it. Besides, the hallmark of the qualitative approach to research is seeing through the eyes of the people being studied (Bryman, 2016) and the placement of premium on the informant's view of the facts.

4.8 Limitations of the study

There are four main limitations that confront this study. Most of these emanate from the attempt to adopt an interdisciplinary and mixed methods approach to understanding the smallholder productivity conundrum in SSA. The first limitation of the thesis relates to the sample size of the quantitative survey. The sample of 32 households for each study community tended to be inadequate for a thorough quantitative analyses to run more robust regressions, which would then enable more robust linkages to be drawn the determinants of maize yields. The limited size of the sample was decided on given the quantum of multidisciplinary data that was to be collected within the period when the crops were in season. This limitation was, however ameliorated by the additional qualitative fieldwork, which shed more light on some of the indications in the quantitative data. Notwithstanding the time lag between the two sets of fieldwork, the additional qualitative field data that was generated gave an in-depth understanding to the yield problem, particularly from the perspective of smallholders. The complementation of the quantitative data with the qualitative one, allowed a certain nuance, which would otherwise not have been unearthed, to come to the fore.

The second limitation relates to data incompleteness, with specific reference to the remote sensing of the plots. The data incompleteness in the remote sensing surveys of plots was due to equipment crashes and weather limitations; the peak of the farming season also comes with a lot of rains and UAVs do not cope so well with water. As a result of three UAV crashes, we were unable to complete three rounds of flights for all plots as was envisaged originally. Despite this, we were able to survey all plots at least once in the course of the farming season between April and July of 2016. Besides the UAV flights, all other segments of data collection went according to plan. The third limitation of the present study relates to having one subplot for each plot instead of multiple subplots. This was not envisaged from the start of the study and though multiplicity of subplots is often recommended to improve the reliability of yield estimates based on crop cuts, it is rarely practiced due to financial and labour demands of such an approach. Given the level of within-plot variability in crop vigour found by the present study, using multiple subplots is not just recommended but ought to be a requirement for a more reliable yield estimation using the crop cuts approach.

Finally, the prospect of upscaling the adoption of the UAV technology on smallholder farms is largely limited at the present in SSA. This notwithstanding, the technology could be just a few years away from widespread use given the benefits inherent in their application in agriculture. The major barrier relates to the cost involved in the initial investment. Despite this barrier, for policies and programmes aimed at improving farm productivity and agricultural modernization, investments of donor funds in a UAV programme would be one of the so-called low hanging fruits that could yield almost immediate and tangible results by serving as a source of farm intelligence to support smallholder decision-making. Besides the few, relatively well-off smallholders, other farmers could form themselves into cooperatives, so that such initial costs would not be overly expensive for them. Overtime, such tools will more than pay for themselves.

5 Synthesis of key findings

> *"So, the way I see it, the maize* [covers] *the cost of the farming and the cassava is our profit"* – JA, male, 74-year-old smallholder maize farmer, Akatawia.

5.1 Introduction

In this section of the thesis, I revisit the four research questions posed in Chapter 1 and present a synthesis of the key findings from the four articles that comprise the thesis. This is then followed with a discussion section, which relates the results from the study to the theories that provided the frame for the thesis. I then proceed to discuss the specific contributions of this thesis. The specific contributions grouped into methodological, empirical, and theoretical contributions. Finally, recommendations for future research are made in the context of the limitations of the present study. The discussions of the main findings of the Article I and, to a lesser extent, Article II will be brief compared to those of Articles III and IV. The reason for this is that Article I is more of a remote sensing paper and may be seen as rather technical and so mainly serves to provide the basis for the subsequent work.

5.2 Summary of key findings

5.2.1 Remote sensing of yields in complex farming systems – Article I

As intimated above, the first paper was mainly to lay the foundation for the entire study. It relates to the first research question, which seeks to measure the accuracy of a vegetation index derived from aerial photos of small farms in estimating crop vigour and yields as compared to in-field methods in complex smallholder farms. The main finding of Article I is that the vegetation index derived from the aerial imageries of plots is as reliable a predictor of crop vigour and yields in complex farming systems in SSA as those derived from high-resolution satellite imagery. This is in line with those obtained by Sibley, Grassini, Thomas, Cassman, and Lobell (2014) on maize fields in Nebraska using Landsat data – 20% and 50% for rainfed and irrigated fields, respectively. Such studies have been, hitherto, virtually impossible in the context of SSA due mainly to satellite data shortfalls relating to cloud cover and spatial resolution *vis-à-vis* the generally small sizes of smallholder farms (Cheng et al., 2016; Wójtowicz et al., 2016). The second shortfall is often overcome with higher-resolution, albeit scarcer, satellite data. Where such data are available, results obtained (Burke & Lobell, 2017) are often similar to those presented in Article I. The advent and application of UAVs as remote sensing platforms significantly overcomes these barriers to crop remote sensing in SSA agriculture.

Another important finding from Article I is that the remote sensing approach as applied in the current study performs better than in-field approaches, which rely on either visual estimation or scoring of crops vigour, or SPAD meter measurement to gauge plant chlorophyll content, and hence health, of crops. The advantage that the remote sensing approach has over other in-field methods for ascertaining crop status is the holistic perspective that the former offers (Jones & Vaughan, 2010). This should thus be preferable to more laborious and time-consuming in-field methods. The achieved results of R^2 = 37% and 39% are relatively strong given the context of the study – rainfed, smallholder farms rather than irrigated, or even experimental plots. This is in light of Sibley et al. (2014) finding that across all methods and sensors tested, yield variation on irrigated fields are more successfully captured than those on rainfed fields; due mainly to the relatively small field sizes and the difficulty with modelling water stress.

Even more important is the finding that the strongest relationship between the derived vegetation index and crop vigour is achieved as early as 5 weeks after planting compared with the SPAD reading which is strongest at 9 weeks after planting, and with visual scores being most reliable at about 12 weeks after planting. This has important implications for the prospect of application of precision agriculture in such complex farming systems. This finding is comparable to those of rice for which the strongest relationship was found at the panicle initiation stages (Swain et al., 2010). Similarly, Piekarczyk et al. (2011) found the strongest relationship between spectral indices and yields for oilseed crops to be at the early stages of flowering. In the light of the above, the findings of Article I, with the strongest relationship between the vegetation index and crop vigour and yields being at about 5 weeks after maize planting, is significant to the extent that it gives promising prospects for further applications, especially in the area of yield prediction.

Yield prediction has important implications in two areas. First, using such a tool, crop inventories could be established, which could then serve as an early warning signal system for potentially poor seasons (Jones & Vaughan, 2010, p. 284). Such an early warning system could be used, for example, to make contingency arrangements to augment grain stocks rather than wait till food shortages occur before remedial actions could be instituted. A second application of yield prediction is that the ability to forecast could form the basis for some form of crop insurance scheme to assist farmers access cheaper loans to invest in their farms. The dearth of agricultural insurance, especially in SSA, has been shown to be one of the major barriers to agriculture financing (Brown, Osgood, & Carriquiry, 2011). This is particularly relevant for West Africa where climate changes continues to have dire consequences for crop yields (Traore, Corbeels, van Wijk, Rufino, & Giller, 2013). With such objective and independent crop yield forecasts, however, traditional insurance entities which, hitherto, would not venture into this area of business due to the inherent risks and uncertainties could now be more amenable to doing business in the agriculture sector. Such applications have important implications for improving food security by minimizing uncertainty that is characteristic of rainfed smallholder production systems.

5.2.2 Plot area loss and implications for yield estimations – Article II

Building on the foundations of the first paper, Article II tackles the second research question, which relates to comparing yield estimates based on farmers' self-reports to those based on crop cuts in the same plots and how much of the disparity is attributable to in-season plot area loss. First, significant loss of plot area during the farming season was found; a range of 3.2 hectares (18%) in Akatawia to 4.5 hectares (30%) of the planted area became unproductive during the farming season. This plot area is substantial given that average maize plot size for individual smallholder farmers in both study communities was about 0.4 hectares. Smallholders are far more likely to experience significant area loss because they tend to cultivate marginal lands and not replace soil nutrients (Reynolds et al., 2015). The substantial area loss – calculated as planted area minus productive area – has crucial implications for yield estimation in the context of smallholder farmers in SSA. While area loss is common on smallholder farms in SSA and complicates yield estimation

(Sapkota et al., 2016), many studies on farm productivity often fail to specify how they define crop area – planted or harvested area – and this has important implications for the yield levels they report (Alston et al., 2010). In this vein, the formulation of the concept of effective plot area becomes key and will be discussed further under the section on specific contribution of this thesis. How smallholder farmers deal with such poor patches ought to have important implications on yield estimation and productivity measurement on rainfed plots in SSA.

Second, Article II also finds significant disparities between farmers' self-reported and crop cut yields; with the former significantly underestimating yields and the latter having the tendency to overestimate them. This finding is in line with others (Carletto et al., 2015; Carletto et al., 2013; Desiere & Jolliffe, 2018) who find substantial inaccuracies in farmers' self-reports resulting from the tendency to round off, variations in measurement units and misreporting – deliberately or otherwise. Reliability of farmer estimates also vary across regions, field area and crop type – with SSA suffering most significant inaccuracies (Fermont & Benson, 2011), higher tendency to overestimate farm area less than one hectare (Carletto et al., 2013) and less accuracy with food crop area compared to cash crop area (De Groote & Traoré, 2005). Overestimation of yields based on the crop cuts – the so-called gold-standard – method in yield estimation is attributable to the substantial within-field variations in crop cover and health. In light of the ubiquity of poor crop patches, especially on rainfed smallholder plots in SSA, yield measurement approaches need contextualizing. Yield estimation methods developed, tested and fine-tuned in other regions may not adequately capture agricultural productivity in SSA (Sapkota et al., 2016). This is important because a fundamental assumption underlying the CC approach to yield estimation is reasonable homogeneity in crop vigour. This substantial heterogeneity brings to the fore the need to define the crop area – whether planted area or harvested area – that is used in studies (Alston et al., 2010). This is also relevant given that plot area often changes throughout the farming season arising from weather damage or unusual economic conditions (Craig & Atkinson, 2013).

My findings of crop cut yield estimates exceeding farmers' self-reported yields are similar to those by Sapkota et al. (2016) and Fermont and Benson (2011). The former study finds that the CC approach consistently overestimate yields as a result of the inherent bias it has when extrapolating results to larger areas from subplots, which generally perform better. There is also the tendency for farmers to omit from their reports crop outputs used as payment for labour or rental as well as deliberately under-report if they perceive the possibility of some form of benefits will accrue to them if they reported poor yields (Fermont

& Benson, 2011). The present finding – of CC yields being on the average higher than SR yields – contrasts those by Gourlay et al. (2017) and Lobell et al. (2018) who find that in Uganda, average SR yields were higher – in some cases, more than double CC yields. Gourlay, Kilic, and Lobell (2019) now attribute this discrepancy to over-estimation by farmers in their self-reports of production, particularly for plots whose area was below the average farm size. Refining yield measurement not only has the potential of improving the reliability of the data that are reported for such complex farming systems but also help isolate and shed more light on the underlying sources of poor crop yields in the region. This is crucial to improving actual productivity on smallholder family farms in SSA.

5.2.3 An integrated approach to unravelling smallholder yield levels – Article III

Article III caters to research question three which relates to the magnitude of contribution of various factors to current maize yield levels and the driving role of socioeconomic factors. Key findings are as follows: First, the factors determining maize yield levels are not consistent across yield measures and study villages. This partly explains why, despite long-standing efforts, there is no consensus on the factors that underlie the observed yield levels and their variabilities. We find that the most important factors determining maize yield levels are timing of planting, inorganic fertilizer use rate, weed coverage, household income level, voluntary labour used, and soil component 4, which is loaded by average soil penetrability and phosphorus content. Of these, maize planting time has the strongest explanatory power. The importance of timing of planting is in sync with those by Adu et al. (2014) and Dobor et al. (2016). The relationship between timing of maize planting and yields is inverse so that there is consistent reduction in yields as planting delays after the first week of rains. Early planting is associated with higher maize yields because it affords the plants the opportunity to utilize the entire growing season and thus maximize yields (Adu et al., 2014). It is particularly important in the face of climate change and climate variability given that younger plants are more capable of enduring dry spells than older ones. Smallholders are aware of the importance of early planting as well as the existence of the so-called ideal planting window and yet continue to extend planting into the month of May. This occurs as a result of some important underlying factors.

Another important finding from Article III relates to the spatial distribution of poor crop patches. The spatial character, especially if studied over multiple seasons, sheds light on the driving forces of such poor patches (Grisso et al., 2009). Analyses of the aerial images shows that poor patches are often concentrated on the borders and edges of maize fields. Poor patches were also more pronounced on ploughed plots compared to non-ploughed ones. In addition to plough lines, field surveys show that poor patches of maize were more severe under large tree canopies. The farmers attribute these to competition from nearby bushes and tree canopies for soil nutrient and moisture. These findings chime with those by Ndoli (2018) who finds that maize emergence rate and yields are severely affected by such competition. The presence and severity of this challenge is usually beyond the purview of smallholders who lease their plots. For example, commercial trees such as *Odum* trees (*Milicia excelsa*) are maintained by landowners for the purposes of social security and will only be harvested in case a sudden need for cash arises. Until this happens, it is the lease holding farmer who suffers the negative consequences of the trees' presence on the maize farm.

Integrating all data sources brings to the fore two main socioeconomic factors – land tenure dynamics and labour limitations – which underpin and drive current yield levels. This finding is in sync with the postulation that socioeconomic factors often drive management and soil factors that, in turn, more directly influence crop yields (Mueller & Binder, 2015; Snyder et al., 2016). These two driving forces may act in isolation or in concert to influence crop yields in complex ways. For instance, the land tenure system in operation in both study villages is predominantly private. Given the patriarchal nature of the society (Lambrecht, 2016) and the importance of land as a factor of production, it is usually bequeathed to all male children from one generation to the next. This leads to continuous division of farmlands among heirs and, consequently, the phenomenon of shrinking farm sizes. As a result, smallholders who have the means to cultivate more than an acre are often forced to do so at multiple locations. Those who have the resources – either for hired labour, volunteer or family labour may be able to prepare all their plots in time for planting (Gianessi, 2013). Others will necessarily have to stagger preparation and planting and thus end up planting outside the ideal planting window. The timing of such time-sensitive management activities as planting, weed control and fertilizer application has been shown to have important implications for crop yields (Beza et al., 2017; Dobor et al., 2016). Operating a number of small maize plots in multiple locations have been shown to cause inefficiencies in maize production. The reasons for the inefficiencies include increased travel time, waste of border spaces, ineffective monitoring, as well as inability to use farm machinery (Wongnaa & Awunyo-Vitor, 2018).

Another important related finding of increasing farmland scarcity is reduction in fallow periods, and consequently reduced soil fertility. The general view among the farmers interviewed is that, if they could afford it, most of them would apply much more inorganic fertilizer on their plots. This is in line with other studies (Ajayi, Place, Akinnifesi, & Sileshi, 2011; Yengoh, 2012) which found limited financial means as a major barrier to fertilizer usage on smallholder farms. Compared to recommended application rates about 120 kg/ha (Assefa et al., 2019) our findings of less than 30 kg/ha in both study villages is woefully inadequate to maintain necessary soil fertility levels. This chimes with the findings of Binswanger-Mkhize and Savastano (2017) who find that in the face of rapidly growing population, SSA farming systems tend to intensify their activities but without adequate quantities of fertilizers to maintain soil fertility levels. Even more interesting is the assertion by a few of the farmers that they perceive, if any, negligible differences in the yields of users and non-users of inorganic fertilizers. While this may be attributed to the comparatively low levels of application, this may point to non-responsiveness of local soils and seeds to fertilizer use. This is important given that the vast majority – more than 75% in both study villages – rely on local and recycled maize seeds, which have been shown to be less responsive to inorganic fertilizer application (Hayami & Ruttan, 1985). This implies that farmers' attitudes, perceptions, and understanding is crucial to dealing with and improving current yield levels.

5.2.4 Smallholder farmer perceptions and attitudes towards yield levels – Article IV

Article IV caters for the final research question, which relates to how smallholders perceive and deal with poor crop patches on their plots. Farmer attitudes and perceptions are fundamental to the extent that their decisions and management activities are based on what they think as much as the resources they can command. Thus, understanding the yield conundrum of SSA will require a more nuanced understanding of farmer decisions and choices and the motivations of these.

As a basis for understanding farmer perceptions, we examined the sources of information that farmers rely on in their decision-making. The sources of agricultural information were categorised into two broad groups: local/community sources and external sources of agriculture information. The key finding here is that a significant proportion – 68% and 66% of the Asitey and Akatawia respondents, respectively – cited indigenous knowledge from ancestors with less than a quarter citing extension officials as their main source of information. Even more instructive is the rating in terms of timeliness and reliability of the various sources; more than half of the sampled farmers rated indigenous knowledge from forbears as the most timely and reliable source of agricultural information in both study villages. Information from extension officers rated a distant second with less than a fifth rating agricultural information sourced from extension officers as the most timely and reliable source. This finding is similar to those of Lwoga, Stilwell, and Ngulube (2011) who find that local sources of information – neighbours, family and friends – were the most important, followed by extension services. It, however, contradicts findings by Brhane, Mammo, and Negusse (2017) in Ethiopia where extension services was the most important source of agricultural information. In their research context, extension services have been well-developed compared to our present study context. Thus, the farmers rating and reliance on agricultural information is context- and content-dependent (Elly & Epafra Silayo, 2013). It is important to note that no one source of agricultural is sufficient in and of itself to meet the information needs of farmers (Brhane et al., 2017) and so an integration of information sources is necessary to provide the needed knowledge base for farmers in order to improve yield levels (Misiko & Halm, 2016).

Given the widespread dependence on indigenous knowledge, it was not surprising that the overwhelming perception of farmers interviewed was that of contentment with current productivity levels. More than half of the farmers interviewed (54%) were of the view that they were getting enough yields, with even a greater proportion (63%) having not attempted to deal with observable poor patches. This notwithstanding, an overwhelming majority (88%) perceived that their plots could yield much more than they are currently yielding and that investments in yield-improving inputs are worth the expense. This is important and similar to the findings of Nigussie et al. (2017) that, among other factors, the level of interaction between farmers and extension workers influences the former's perception of the severity of soil erosion of their plots. While the low levels of fertilizer application reported in Article III is largely attributable to the limited financial means in the household at crucial stages of the farming season, one can also argue that farmers do not feel adequately incentivised and motivated to invest their limited resources on their farms. This is as a result of perceiving little difference between use and non-use of inorganic fertilizer on their plots (Kansiime et al., 2019). Thus, farmers are not keen on borrowing money even on a short-term basis from local money lenders due to the often unreasonable and exploitative terms associated with such financial supports.

Rather, farmers perceive the preponderance of poor patches are unavoidable and tend to adopt an attitude of risk minimization and aversion. Thus, instead of investing already limited resources to improve current yields under such unpredictable and risky contexts, farmers would rather cultivate other crops that are more tolerant of current conditions or invest off the farm in ventures they perceive as less risky (Moyo et al., 2012). This finding of increasing diversification both on and off-farm is in sync with Dzanku (2019) who finds that rural households often have a portfolio of economic activities, which together constitute their livelihood. This does not, however, mean that they are quitting agriculture altogether. Rather, smallholders aim at yield stabilization even if at low productivity levels in order to diversify. Their level of diversification however is influenced by the agricultural potential of the location and market dynamics (B. Davis, Di Giuseppe, & Zezza, 2017; Yaro, 2013) as well as opportunities available for and profitability of off-farm activities (Jirström et al., 2018).

Another important finding is the differences in attitudes of farmers under different land tenure systems. From both study villages, farmers who inherited their plots and are, thus, outright owners, tend to be more willing to invest in the long-term quality of their plots. Thus, rather than trying to maximize yields in the short term without much concern for the long-term implications of the activities on the plot, as was the case with some leaseholders, owners often aim for yield optimization and stabilization (Benneh, Kasanga, & Amoyaw, 1997; Codjoe, 2006). This category of farmers also tends to eschew farm activities such as heavy weedicide use, which they perceive to be detrimental to the long-term welfare of their soils.

From the foregoing, there are a several processes unfolding within this sector that requires careful study in order to understand the medium- to long-term future of small farms. The preponderance of relatively small plot sizes of such an important staple crop as maize – averaging less than half a hectare – despite the availability of more than two hectares of fallowed farmland per household deserves scrutiny. Equally important, the finding of satisfaction and indifference to the preponderance of poor patches on maize plots is intriguing. While this attitude may appear counterproductive or even irrational, it is grounded on their experience and rational assessment of the risky environment within which they operate (Netting, 1993).

5.3 Relating results to theory

Juxtaposing population changes and food production and productivity trends brings to the fore some interesting dynamics. Taking Ghana as an example, the national population has almost quadrupled from 6.7 million in 1960 to more than 24.7 million by 2010 (GSS, 2013; Owusu, 2010). Agricultural production and productivity has not seen similar levels of growth in the same period (Dzanku et al., 2015; FAOSTAT, 2019). Even more important, the tools and technologies used in agriculture in this region has not seen any significant changes with agriculture still predominantly rudimentary. Boserup's theory posits that population growth motivates intensification of agricultural productivity. This intensification results from technological advancements in the tools and methods of farming (Boserup, 1965, 1981; Fischer-Kowalski et al., 2014). This process occurs through a mechanism whereby population pressure triggers the development and use of technologies and strategies to increase food production commensurate with demand (Turner & Fischer-Kowalski, 2010). The theory also features a feedback loop whereby technological advancements in agriculture leads to further population growth (Boserup, 1981). Taken in these broad terms, one may be tempted to argue that the theory fails to adequately account for the Ghana agriculture situation. It, however, distinguishes three kinds of intensification that can occur.

The kind of intensification unfolding in SSA and more specifically in the study villages is the third type whereby population growth leads to changes in the patterns of land use but productivity in the non-agriculture sector remains low (Boserup, 1965, p. 65). The result is the continuous reliance on rudimentary tools so that despite the increased demand of a rapidly growing population, agricultural production and productivity is not growing commensurably. The logical consequence is the inordinate dependence on food imports (De Graaff et al., 2011). However, where the productivity in the non-agriculture sector improves, the second kind of intensification as posited by the theory can take place. This entails changes in the pattern of land use and the tools and technologies employed in agricultural production, leading to rising productivity levels. This growth in productivity is expected to occur in both the agriculture and the non-agriculture sectors of an economy due to the forward and backward linkages between the two sectors (Haggblade, Hazell, & Reardon, 2010). While this is ideal, the tools alluded to must not necessarily be manufactured in specific countries or regions given the increasingly globalized nature of world economy. More pertinently, depending on the context, certain technologies may be more relevant than others. The results from this study shows that while tools like tractors are useful, more relevant technologies include improved seeds and appropriate levels of fertilizer usage.

Furthermore, Boserup's hypothesis that simple societies with sustained population growth stand a better chance of launching into a process of genuine economic development (Boserup, 1965, p. 106) has two important caveats. First, such a society must not already have very high population growth rates or must not already be densely populated. Population density may be arithmetic – the number of people per square kilometre of land, physiological – number of people per arable square kilometre of land; and agricultural – the number of farmers per square kilometre. The theory however does not define the type of population density and so it is difficult to determine the violation or otherwise of the condition. However, given the dominance of smallholder farmers, it is fair to extrapolate that agricultural population density would be high. Besides, the high arithmetic population density in the study districts indicates that this condition is likely violated. Further, all extant literature shows very high population growth rates both at the continental as well as the national level (PRB, 2017).

The second caveat for such a society to be able to undergo a sustained socioeconomic development is that farmers should be able to undertake significant investments on the farm as well as undertake major changes in land tenure (Boserup, 1965, p. 65). My results show that required investments are lacking and that smallholder farmers would rather invest their meagre resources into ventures they consider less risky off the farm. Smallholder farmers would shift into investing in new technologies and innovations only if land and labour dynamics induced them into doing so (Hayami & Ruttan, 1985; Turner & Fischer-Kowalski, 2010). Current dynamics are not incentivising enough for smallholders to adopt modern factors, which are productivity-enhancing (Schultz, 1964).

Within the context of my study, the third phase of tenure dynamics that Boserup postulates appears to be unfolding. This entails the predominance of modern tenure whereby most smallholders rent farm plots and then pay money not only for labour but also for non-agricultural essentials leaving little left to invest in industrial agricultural inputs (Boserup, 1965, pp. 78-79). The theory attributes the use of insignificant quantities of industrial inputs to the low stages of economic development of the society to which the study communities belong. What this demonstrates is that population growth and market access are necessary but inadequate conditions to induce required levels of on-farm investments.

It is important to also note that the results show that the sheer existence of such technologies does not guarantee that adequate quantities would be used to bring about the needed changes in agricultural production and productivity. The induced innovation theory (IIT) postulates that every region or country needs to have the capacity to generate ecologically-suitable and economically-viable agricultural technologies (Hayami & Ruttan, 1985; Ruttan, 1977). At the initial stages of development, such technologies do not have to be industrially advanced and complex like tractors and combined harvesters.

Within my study context, such technology as improved seeds and fertilizers are much more relevant. The IIT further holds that the causal sequence leading to the inducement and use of such innovations starts with a change in factor scarcities, which in factor markets reflect in changes in factor prices. It is the relative factor prices that determine the optimal technological bias from the perspective of farmers. As rational agents (Jirström, 1996), farmers are replacing more expensive factors with less expensive ones to their advantage.

A key caveat for the IIT is that the agricultural sector must also be able to adapt to the new factor and product prices. That is, in a context where product prices do not change in response to the changes in factor prices, farmers are accordingly not expected to respond. The land tenure system in operation in my study context ensures that a significant proportion of smallholders do not pay rent for farmlands. This category includes those who inherit lands from progenitors and those who access state-lands informally. Given the relatively high or increasing cost of labour, it is rational for farmers to be biased towards labour-saving technologies. An important example of the labour technology in the context of the present study is the widespread proliferation of the labour-saving technology of knapsack sprayer for not only weed control but even during plot preparation with significant implications for crop yield levels. In the same token, it is also rational for farmers in countries or regions with relative high fertilizer prices but relatively low agricultural produce prices to rely on traditional seeds and use limited levels of fertilizer (Hayami & Ruttan, 1985). The finding of negligible differences in yields between users and non-users of fertilizer, at least from the perspective of smallholder farmers, is instructive.

It is important to note, however, that even in the same villages, technological adoption processes proceed in complex ways. Farmer motivations and decision-making is grounded in and influenced by their specific circumstances. The concept of labour-consumer balance by (Chayanov, 1966) also helps explains how the smallholder household's dualistic objective of satisfying family consumption needs while minimizing the drudgery of labour play out in the present study context. While a gamut of factors such as size of landholding, crop grown, and diversification thereof, markets, interest rates, relative population density, and availability of off-farm work all affect this balance, the household size and composition occupy a central place for Chayanov. Thus, the decision to self-exploit – work more intensely for more hours – may not be appealing if farmers perceived that this would not lead to extra produce that would contribute to improve the welfare of the household.

In the light of this, my finding of increasing diversification in order to maintain a certain constant level of wellbeing is important. Indeed, productivity *per se*, is rarely an end in itself. The household's own sustenance is the primary preoccupation of the farming enterprise. Thus, rather than seek to maximize yields and profits, smallholder farmers often opt for the rational and satisficing attitude of stabilized yields and directing remaining resources – human, physical, financial – into other areas in order to secure a certain minimum, socially-accepted personal and household welfare based on differing socioeconomic milieus (Dorward et al., 2009; Netting, 1993). This predisposition is based on experience accumulated over several years and generations (Ruthenberg, 1971) in contexts of poorly functioning agricultural input and output markets.

Certain fundamental assumptions of the Chayanovian theory make its application in the present study context fraught with challenges. The characterization of smallholders as self-sufficient, with marginal market participation, non-utilizing hired labour and operating in a context of land abundance (Chayanov, 1966; Hammel, 2005) does not inhere in this study context. On the contrary, the present findings show smallholder farmers operating under severe land constraints in terms of availability. This culminates in multi-location of plots, which contributes to delay in time-sensitive farm activities such as planting (Wongnaa & Awunyo-Vitor, 2018). Similarly, with regards to labour, we find that labour availability is a key yield determining factor. Households with a more economically active labour force and those that can access voluntary labour would thus be expected to achieve higher yield levels. Access to voluntary labour, however, depends on the social capital that the household commands. It is within this framework that the sustainable livelihood approach becomes relevant.

The sustainable livelihood approach (SLA) offers a valuable lens for analysing complex rural livelihoods given its fundamental commitment to locally-embedded contexts and placing of premium on the perspectives of the poor and marginalized in society (Scoones, 1998). The SLA thus emphasizes the importance of understanding people's priorities and motivations and discourages the assumption that individuals and households are always completely dedicated to maximizing their production and incomes (DfID, 1999). It is within this perspective that the finding of the attitude of contentment with current yield levels should be understood. An excerpt from an experienced 74-year farmer in Article IV that reads: *"If you are looking at only the maize, then you might say we did not get adequate yields from the plot. But if you are looking at the plot as a whole and the fact that we also got cassava and other crops from the same piece of land, then overall, I am happy with how much I am getting from the farming…the way I see it, the maize is the cost of the farming and the cassava is our profit"* is instructive. It not only shows satisfaction with current productivity levels but also attainment of a certain minimum threshold of welfare by considering the farm as a whole. This also explains the attitude of risk aversion and minimization.

The crux of the SLA is that individuals and households require a range of resources – assets – to achieve a positive livelihood outcome (DfID, 1999). However, households have differential capabilities and resources available to them to irk out a living (Allison & Ellis, 2001). They also operate within an institutional framework influenced by land tenure, laws, rules, customs and traditions, which in turn govern and shape not just access to various forms of capitals but also terms of exchange and returns to a chosen livelihood strategy. While some resources – roads as means of transportation to markets – are publicly accessible, access to others such as state-expropriated lands are determined or at least influenced by certain attained positions in society. Still, access to other resources is largely private – radio to access timely agricultural information, for example. A key finding relates to differing attitudes of smallholder farmers under the various tenure arrangements. For example, farmers who inherited their plots and are thus outright owners of their farmlands tend to be more interested in the long-term sustainability and viability of the soils and land. Such farmers eschew farm practices such as heavy herbicide usage, which they perceive to have adverse effects on soil health in the long run. Smallholders who only rent their plots for a couple of seasons tend to be more interested in recovering their investment by extracting maximum yields even if this means discounting the future (Benneh et al., 1997; Codjoe, 2006).

Furthermore, in times of harsh socioeconomic conditions, households with access to appreciable levels of various categories of capital have the room to adapt their livelihood strategies to ensure that they are not unduly negatively impacted (Chambers & Conway, 1991). This is possible due to the feedback loop between livelihood outcomes and strategies. For such relatively well-off households, strategies include hoarding and protecting accumulated assets including food. It is possible to then re-invest the increased income into other ventures that afford better livelihoods and propels such individuals and households into a cycle of accumulation. This is the case with the smallholder farmer who operates his own taxi (excerpt reproduced in Article IV). For households with limited access to the various forms of capital, however, their coping strategies often entail stinting by reducing consumption levels, depleting remaining assets or diversifying by seeking new sources of food or spreading work activities and income sources. Such remaining assets could be the last Odum tree on their land, last couple of poultry and/or ruminants or even offering labour on other people's farms. Such strategies also feedback into the vulnerability levels in the long term. For example, a farmer who is looking to make some money by working on other farmers' plots during the preparation stages of the season might have the preparation of his/her own plot delayed with significant consequences for the yield levels they obtain. This then leads to a vicious cycle of deprivation.

The nature of agriculture that evolves and is practised, including the methods of soil fertility maintenance, technology adopted, and the level and type of intensification are all influenced by not only the agroecological but also the socioeconomic milieus within which smallholders operate (Binswanger-Mkhize & Savastano, 2017). Smallholder farmers contend with multiple challenges that are interlinked in complex ways. These range from rapidly growing populations (and thus increasing mouths to feed at the household levels) to poorly developed inputs and outputs markets and limited financial means. Among others, these challenges drive farmers towards a peculiar kind of agricultural intensification that is labour-driven with limited use of yield-enhancing technologies. Diversification – on- and off-farm – is largely to ensure that farmers attain at least a certain minimum level of consumption. Smallholder households' ability to attain and maintain a socially-acceptable standard of living varies from one household to the other. There is, therefore, the need for nuance in our understanding of smallholders in SSA in order to be able to exploit the advantage that current low levels of crop yields affords in terms of room for significant growth in productivity.

5.4 Specific contribution of the thesis

The most significant contributions of the present thesis are outlined in this subsection. The contributions are organized into themes of methodological, empirical, and theoretical contributions.

5.4.1 Methodological contributions

The thesis makes four key contributions. First, it develops a novel method and approach for extracting a vegetation index from a UAV imagery in such complex farming systems. This could prove a significant milestone in the application precision agriculture tools in SSA. Remote sensing of crops using high resolution satellite imagery is already a well-developed field in advanced agricultures of Europe and North America. Recent advances in computerization and miniaturization have now paved the way to avail such tools as UAVs at economic rates in developing agricultures. Hitherto, the predominantly small sizes of smallholder plots impeded the application of such technologies. While Burke and Lobell (2017) use of ultra-high resolution satellite data in Western Kenya demonstrate the promise that finer resolution remote sensing data hold for the agricultural intensification efforts in such complex farming systems, Article I demonstrates the utility of UAV as a remote sensing platform in such complex farming systems. The strength of the use of this platform is its ability to, in the long-term, fill the spatial resolution gap between manned aircrafts and the more laborious in-field method of ascertaining crop status through transect walks.

The second methodological contribution of the thesis relates to not just re-echoing calls to revisit current measures of farm productivity (Sapkota et al., 2016), especially in the context of complex SSA smallholders but providing a strong basis for such calls. The basis is derived from the finding of significant plot area loss during the farming season and the demonstration of substantial changes in yield figures based on the different areas. Article II additionally makes cogent arguments against reliance on farmers' self-reported plot area data as well as the GPS-measured plot area. Its findings demonstrate that even the so-called gold standard would have to be undertaken multiple times in order to accurately estimate plot area. The use of remote sensing data, at least for validation purposes, potentially reduces the cost that would be incurred by these multiple measurements of plot area in farm surveys. In the same vein, the findings of significant area loss contribute and break new frontiers on the age-old farm size-productivity debate.

The third methodological contribution relates to the use of an integrated approach – integration of both methods and data – to unravel the factors that impinge current yield levels. Given that smallholder farming is characterized by complexity and heterogeneity, a nuanced understanding ought to integrate biophysical, socioeconomic and cultural milieus in which farmers operate (Mueller & Binder, 2015). The combination of methods and data avoids the limitations inherent in discipline-focused studies given that no one factor, or cluster of factors can comprehensively explain yield limitations. In Article III for example, the statistical analyse showed timing of planting, inorganic fertilizer application rate, household income level, labour limitations and weed control were key explaining factors. However, ocular examination of the aerial photographs shows that poor patches of maize crops were most prevalent on the borders of fields. The photo-elicitations interviews (PEIs) based on the aerial photos further helped to unravel why the poor patches are concentrated in certain regions of maize fields as well as why farmers continue to plant beyond the ideal planting window despite their knowledge of the yield-reducing effects of this. Triangulation of data and methods thus helps to unravel the underlying role of socioeconomic factors relating to land tenure and household labour, which are often not considered in such studies (Beza et al., 2017).

The fourth methodological contribution of this thesis relates to the use of aerial photographs in qualitative interviews. While visual research methods such as PEIs are less frequently employed, their use "evokes deeper elements of human consciousness than do words" (Harper, 2002, p. 13) by stimulating interviewees to engage visually with their settings and remember situations they may have forgotten (Bryman, 2016) as well as elicit tacit knowledge (Pain, 2012). The synoptic view that aerial photographs of farms offer farmers is a peculiar view of their plots. This helped enhance the richness of the data by peeling extra layers of meaning by enhancing interviewees' ability to express their practical and latent knowledge through attribution and association. To the best of my knowledge, the use of drone imagery is this manner is novel.

5.4.2 Empirical contributions

The thesis makes four important contributions. First, the finding that the remote sensing approach using aerial photography is a timelier and more reliable predictor of crop health and yields compared to other in-field approaches for ascertaining crop status. This is despite the multiple confounding factors relating to the complexity and heterogeneity that characterizes smallholder farms in SSA. This contributes to opening the door wider for the application of precision agriculture tools in such farm systems.

The second empirical contribution of the present thesis relates to the finding of significant plot area loss in the course of the farming season. Area loss – ranging from 15 to 30% in our study context – is not necessarily a novel finding (Reynolds et al., 2015). While some have suggested undertaking area measurement multiple times in the course of the farming season (Craig & Atkinson, 2013; Fermont & Benson, 2011), this can have significant cost implications for field surveys. The use of aerial photography of plots to determine the effective area of plots becomes important. This is particularly so where farmers are willing to forgo significant portions of plots because they are not paying rent *per se*. This notwithstanding, such farmers are likely to report the entire plot area as their farm size in surveys. This brings to the fore the need for studies to define the type of area used for yield estimation and analysis.

The third empirical contribution relates to the underlying role of socioeconomic factors as factors driving crop yield levels. In Article III, I go beyond the immediate management factors and even timing of these and their influence on yields (Berre et al., 2017; Beza et al., 2017; Carter, Melkonian, Steinschneider, & Riha, 2018) to analyse how underlying socioeconomic factors such as tenure and associated security it engenders influence farm management, and by extension, yields. It thus sheds more light on the yield conundrum confronting SSA. It also helps us understand how tenure dynamics influence smallholders' investment behaviours and decisions. Additionally, the received literature indicates that one of the main factors limiting fertilizer usage in SSA is the lack of adequate purchasing power in smallholder households at crucial stages of the farming season. The present study goes a step further to explain smallholders' reluctance to resort to borrowing from local financial markets – the over-exploitative conditions often attached to such financial assistance. Thus, while smallholders are very much aware of the potential benefits that could accrue from fertilizer application, they eschew such intensification efforts or pursue agricultural intensification without the necessary inputs for these utilitarian reasons.

The final empirical contribution of the present thesis relates to the findings of an attitude of contentment to current yield levels in Article IV. It has been well-established that smallholder farmers are not always minded towards yield maximization (Chayanov, 1966; Schultz, 1964).They are often more strongly driven to attain and maintain a certain minimum, socially-acceptable consumption level and will pursue this using whatever resources and strategies at their disposal. Their attitude is also borne out of their years and intergenerational knowledge and experience of the environments and a rational evaluation of the constraints and risks they operate within on a daily basis.

5.4.3 Theoretical contributions

The thesis makes critical additions to the Boserupian and the Chayanovian theories by, first, drawing a linkage between tenure type and security on the one hand and smallholders' investment behaviour on the other hand. Boserup (1965, p. 91) explains investment incentives under modern land tenure dynamics in which the economy is at a low stage of industrialization. Boserup posits that agriculture in such rural communities is likely to use only meagre amounts of inputs and with predominantly rudimentary tools. The present study goes further to untangle the explanations for such decisions of smallholders. The tag of smallholders as being unproductive is based on three main assumptions: that they use too much labour, that they do not produce adequate surpluses for the market, and that they do not make rational and economic decisions about production and innovations. While previous studies such as Schultz (1964) and Netting (1993) have already questioned such misleading notions, this thesis presents renewed evidence to support the repudiation of such outdated worldviews. The study has shown that even where smallholders behave in seemingly counterproductive ways, they often have a rational basis for their decisions and choices. These rational decisions are, in turn, based on honest, even if subjective, assessment of their milieu.

5.5 Recommendation for future research

Three areas of future research related to the present study are worth pursuing. First, the importance of the smallholder farmers in terms of the larger national economy is not in doubt. Their importance manifests in their contribution to aggregate production and thus food security, and employment. However, only meagre investments are flowing into the agriculture sector. On the other hand, it has been shown here that farmers would rather invest in less risky, more rewarding ventures off-farm while aiming to stabilize yields on the farm. Additionally, given the customary and economic value that land holds, it is common to find indigenes who migrate out of the rural areas still holding onto their inheritance in land rather than sell or even give such lands out on long-term leases. This is informed by the belief that land is not just a factor of production but also proof of heritage. These tenure dynamics have important implications for the sustainability of smallholder farms. Investigating this is crucial for the prospects of increasing food production by between 70 and 120% in order to meet envisaged growth in food demand arising from the continuously growing population in SSA as well as the changing diets of an increasingly more urban and prosperous population.

A second area related to the present study worth investigating relates to the implications of the increasingly widespread use of herbicides on crops, livestock, weeds, and other biological organisms. A great majority of the farmers interviewed, apart from two, relied on chemical methods to control weeds as well as during plot preparation. From the overall sample, chemical weed control has become most common among farmers. Factors contributing to this proliferation include limited labour availability in the face of the need to cultivate larger plots due to loss of soil fertility, and the spread of grassy weeds. A worrying consequence of the widespread use of herbicides is the development of resistance to these chemicals. Some farmers have, as a result, resorted to using a cocktail of herbicides. This is a worrying trend given the finding by others of this practice on crop vigour and final yields (Krenchinski et al., 2018). This implies that not only does herbicide blending affect within-plot crop vigour but also, ultimately, yields could be affected if more than two of them are used. Despite the ubiquity of the use of herbicides to control weed infestation, a few farmers who take the deliberate decision not to use herbicides do so out of concern for the health implications of these chemicals on crops and their possible effects on residual crops such as plantains and cocoyams as well as other biological organisms like snails and mushrooms. Such farmers, thus, desist from their application due to the concern for the long-term sustainability of their plots. Thus, smallholders, in their bid to reduce drudgery and reallocate household to other more productive and less risky sectors of the household economy have been found to have substantially increased their reliance on herbicides for controlling weeds. This is an area that warrants further study in our quest to ensure sustainable intensification in developing agricultures.

Finally, the relatively better performance of the remote sensing approach at an early stage of the season when complicating factors – weeds, intercrops – are minimal implies that future studies that apply the developed approach on experimental rather than farmers' own plots could demonstrate the actual potentials of the UAV system on predicting yields. Such controlled experiments could be carried on plots with differing levels of weed infestation, pure-stands versus maize plots intercropped with cassava, groundnuts, green beans, among other common intercrops. The methodology used in Article I could also be applied on crops other than maize. In a future research, rice (*Oryza sativa L.*) would be a suitable target crop for two main reasons: first, compared to maize, rice is usually cultivated as a single crop and on larger areas. Thus, most of the shortfalls regarding intercrops and small plot sizes would be minimized. Second, rice fields are often submerged for large periods of the growing season and thus inaccessible. The remote sensing method used in Article 1 would be appropriate for ascertaining within-field crop vigour variability and based on this, appropriate remedial actions can be undertaken. Thus, despite the importance of maize as a staple, rice is equally growing in importance in SSA countries and this is exemplified by their increasing import expenditure on that cereal.

6 Conclusions

> "*No country has been able to sustain a rapid transition out of poverty without raising productivity in its agricultural sector"* – Peter C. Timmer, 2005, in Agriculture and pro-poor growth: An Asian perspective.

The above quotation elegantly captures the historical importance of agricultural development as a major vehicle for achieving and sustaining economic growth that leads to significant poverty reduction. I dare say that there is near-consensus on the poverty-reducing effects of a productive agricultural sector. What is still a subject of strong debate is the ability of smallholder family farms to perform this role effectively. Despite the increasingly open nature of the world trade system and the continued agricultural protection enjoyed by farmers in more developed agricultures, smallholder farmers continue to play critical roles in the economies of developing countries such as Ghana. Although it has recently been overtaken by the services sector in terms of contribution to the national GDP, agriculture remains a key sector of the Ghanaian economy. It is still the largest employer – more than half of the active labour force is engaged in it. This is largely unsurprising given that it is mostly undertaken on a smallholder basis – about 90% of the farms are less than two hectares in size.

A major leg of the argument of the school of thought that expresses pessimism of the ability of smallholder agriculture to play the important role of spurring economic growth is the low productivity that characterizes such farm systems. This position is based on three main assumptions: that smallholders use too much labour, do not produce adequate surpluses for the market, and that they do not make rational and economic decisions about production and innovations. This thinking has been given further impetus by the continuously growing population in developing countries, especially those in SSA, and the attendant expected additional demand for food.

It is against this background that I aimed to augment present understanding on crop productivity levels on smallholder farms in resource-poor contexts. This was achieved by showing the limitations of current methods of yield measurement, unravelling the factors – both direct and underlying –

contributing to current yield levels, and analysing farmers' perspectives on their current yield productivity levels. This entailed the use of cutting-edge remote sensing of farm plots using unmanned aerial vehicles and the less frequently used photo-elicitation interviews to supplement the more traditional field and household surveys.

For starters, I argue, based on the findings in Article I, that the remote sensing approach as used in this thesis is a more reliable and timeous method for ascertaining crop status and yields even in such complex farms. I therefore agree with the position of Zhao et al. (2007) that remote sensing could be key to improving agricultural statistics in the near future. Using this as a basis, I find in Article II strong grounds to call into question the applicability and reliability of yield measurement methods we currently consider as gold standard. The degree of plot area loss during the farming season is disturbing. While area is common among smallholders farmers as they tend to cultivate marginal lands and not adequately replace soil nutrients (Reynolds et al., 2015; Sapkota et al., 2016), many studies on farm yields often neglect to define area – whether planted or harvested area. This has important implications for yield levels that are reported (Alston et al., 2010). Thus, yield measurement approaches may work quite well in some settings and yet fail to adequately capture agricultural productivity in other regions. Improving yield measurement serves two purposes: first, it enhances the reliability of data that are reported for such complex farming systems, which is critical for policy formulation; and second, it helps improve our understanding of the constraints to improving crop yields.

Based on the findings in Article III, I conclude that the factors driving yield levels are inconsistent across yield measures and villages. This implies that a one-size-fits-all approach is not recommended and that efforts to tackle the historically low yields should be context-specific. While the timing of management activities like planting and weed control as well as the quantity of inorganic fertilizer applied were key direct drivers of yield levels, I argue that they are underpinned by some important socioeconomic factors. Key among these were land tenure dynamics and limitations relating to labour. As a result, much of the intensification observed on the farms is labour-driven. Crucially, sweeping changes in land tenure must be undertaken in such contexts in order to stem and even reverse the process of shrinking farm sizes, which is contributing to, among others, delayed planting. Contentment among farmers of their current productivity levels (Article IV) supports the view that smallholder farmers are not always minded and motivated to maximize yields. Attaining and maintaining an acceptable consumption level is a more pressing need. Often, this requires diversifying the sources of food, work activities and income.

Overall, for agriculture to play the historically crucial role in the economic growth of now developing countries as it did in others, there is need for recognition of the fact that the nature and function of smallholder farming is unique. Given its contribution – to employment, GDP, and food security – the role of smallholder farming in the economic growth of such developing countries cannot be overemphasized. In our quest to modernize methods of productions in order to improve productivity, it is important to put as much emphasis on farmers' perceptions and attitudes as we often put on yield-enhancing technologies. This is because attitudes and perceptions drive on-farm investments. As far as smallholder farmers in such resource-poor contexts are concerned, meeting future needs is important but immediate survival is indispensable.

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List of annexes

Annex 1: Household Survey Questionnaire

Greetings! My name is Ibrahim Wahab. I am a PhD student at Lund University. We are undertaking a study dubbed Yield Gap Project, a continuation of the Afrint project which has been on going in this area since 2002 and in which you were are a participant. In the current Yield Gaps project, we would like to understand factors causing low yields of maize in this community.
We are conducting a household survey and information collected will be reproduced as a report which will be shared in a workshop so that other farmers also understand the causes of low maize yields and measures to put in place to improve productivity. This information will also enable me to write a PhD thesis as part of my studies. I hereby seek your permission and time to carry on with this interview which will last approximately 30-45 minutes. I would like to assure you that information collected will be used purely for academic purposes and that your name will neither appear anywhere in the thesis or report nor anywhere else such that would be able to trace the information you provide back to you.
You may withdraw at any time and we will respect your right to decline to answer if there are specific questions you would prefer not to answer. Do we have your permission to carry on?
f001. Respondent consent…………………….
Enumerator details
f002. Enumerator name
f003. Date
Respondent details
f004. Household ID
f005. Country
f006. District
f007. Village
f008. Name of respondent
f009. Age of respondent
f010. Gender of respondent
f011. Education level
f012. Phone number of respondent:
Household head details
f013. Name of household head

f014. Age of household head
f015. Gender of household head
f016. Education level of household head
Household characteristics
f017. Total number of members
f018. Number of males 16 and above
f019. Number of females 16 and above
f020. Number of children below 16 years
Farm details
f021. Total acreage of the household
State the unit
f022. Size of land allocated to food and non-food crops
State the unit
f023. Size of land allocated to compound and grazing
State the unit
f024. Size of land allocated to fallow land
State the unit
f025. Size of land allocated to woodlots and trees
State the unit
Common crop 1
f026. Common crop
f027. Group type
f028. How do you utilize the crop?
f029. Proportion for consumption
f030. Proportion for selling
Common crop 2
f031. Do you have another common crop?
f032. Common crop
f033. Group type
f034. How do you utilize the crop?
f035. Proportion for consumption
f036. Proportion for selling
Common crop 3
f037. Do you have another common crop?
f038. Common crop
f039. Group type
f040. How do you utilize the crop?
f041. Proportion for consumption
f042. Proportion for selling
Common crop 4
f043. Do you have another common crop?
f044. Common crop
f045. Group type
f046. How do you utilize the crop?

f047. Proportion for consumption
f048. Proportion for selling

Common crop 5

f049. Do you have another common crop?
f050. Common crop
f051. Group type
f052. How do you utilize the crop?
f053. Proportion for consumption
f054. Proportion for selling

Common crop 6

f055. Do you have another common crop?
f056. Common crop
f057. Group type
f058. How do you utilize the crop?
f059. Proportion for consumption
f060. Proportion for selling

Common crop 7

f061. Do you have another common crop?
f062. Common crop
f063. Group type
fo64. How do you utilize the crop?
f065. Proportion for consumption
f066. Proportion for selling

Income sources

f067. Source of non-farm income
f068. Other source of income
f069. Proportion of farm income
f070. Proportion of non-farm income

Plot information

Household ID ……………………...
f071. Name of operator
f072. Age of operator
f073. Gender of operator
f074. Education level of operator
f075. Family role of the operator

Crop history and cropping pattern

f076. Years since the plot was brought cultivation
f077. Year 1
f078. Season
f079. Crop
f080. Season
f081. Crop
f082. Year 2
f083. Season

f084. Crop
f085. Season
f086. Crop
f087. Year 3
f088. Season
f089. Crop
f090. Season
f091. Crop
Planting
f092. Method of planting maize
f093. Time of planting maize
f094. Time of planting intercrop
f095. Who makes decision on planting?
f096. Kind of labour used
f097. Proportion of hired labour
f098. Proportion of family labour
f099. Total cost of hired labour for planting
f100. If family member, who was involved 1
f101. Equipment used for planting
f102. Maize type
f103. Which maize variety did you use?
f104. Amount of seed in kilograms, state the units
f105. Source of seed
f106. Availability of maize seed
f107. The total cost of maize seed
f108. Intercrop
f109. Intercrop variety
f110. State the time of planting intercrop
q111. Method of planting intercrop
f112. Who makes decision on planting of intercrop?
f113. Kind of labour used
f114. Proportion of hired labour
f115. Proportion of family labour
f116. Total cost of hired labour for planting intercrop
f117. If family labour, who was involved?
Land preparation
f118. Method of land preparation
f119. Time of land preparation
f120. Decision on land preparation
f121. Labour used for land preparation
f122. Proportion of hired labour for land preparation
f123. Proportion of family labour for land preparation
f124. Total cost of hired labour for land preparation
f125. Who is involved in land preparation 1

Fertilizer application
f126. Did you use inorganic fertilizer?
f127. Number of fertilizer application
f128. Fertilizer inorganic type 1
f129. Time of application
f130. Quantity of application, state unit
Fertilizer application 2
f108. Decision on fertilizer application
f109. Labour used for fertilizer application
f110. Proportion of hired labour
f111. Proportion of family labour
Cost of hired labour organic fertilizer application
f112. Who was involved in the second round of fertilizer application?
Fertilizer application 3
f116. Did you use organic fertilizer?
f117. Number of applications of organic fertilizer
f118. Type of organic fertilizer
f119. Time of application
f120. Quantity of application, state the local unit
Fertilizer application costs and decisions
f130. Decision on fertilizer application
f131. Labour used
f132. Proportion of hired labour used
f133. Proportion of family labour used
f133. Total cost of hired labour for organic fertilizer application
q134. Who was involved 3?
Weed control
f135. Did you practice weed control?
f136. Number of times for weed control
f137. Who made decision on weed control?
Number of weed control
f138. Method of weed control, weed control costs and decision
f139. Time of weed control
f140. Labour used for weed control
f141. Proportion of hired labour
f142. Proportion of family labour
f143. Total cost of hired labour for weed control
f144. Who was involved?
f145. Type of herbicide used
f146. Amount of herbicide used, state the local unit
f147. Equipment used for weed control
Irrigation
f148. Did you practice irrigation?
f149. Time for irrigation control

f150. Irrigation method
f151. Water source
f152. Labour used for irrigation
f153. Proportion of hired
f154. Proportion of family
f155. Who was involved?
f156. Equipment used during irrigation
Soil and water control measures
f157. Have you planted any crops to help control erosion on this plot? State the crops
f158. Which other erosion control measures do you have on this plots other than crops?
f159. How do you utilize crop residue?
Thank you

Annex 2: Plot Survey Questionnaire

Household ID……………………………..
f006. Country
f007. District
f008. Village
f009. Household ID
Plot details
f010. This household is household ID number:
f084. Plot Number
f085. Write HHID for the plot
f086. Name of operator
f087. Age of operator
f088. Gender of operator
f089. Education level of operator
f090. Family role of the operator
Crop history and cropping pattern
f091. State the number of Years since the plot was brought into cultivation
f092. Cropping pattern for recent year (2015)
f093. Season
f094. Crop
f095. Season
f096. Crop
f097. Cropping pattern for Year (2014)
f098. Season
f099. Crop
f100. Season

f101. Crop
f102. Cropping pattern for Year (2013)
f103. Season
f104. Crop
f105. Season
f106. Crop

Land tenure

f107. How did you acquire this plot?
f108. If rented in land, how much money did you pay?
f109. State the year in which the plot was rented

Land preparation

f110. How many times did you prepare land in the current season of maize production?

Land preparation method, decision and costs

f111. Which method of land preparation did you use?
f112. When was the time for land preparation?
f113. Who made decision on land preparation?
f114. Which Labour did you use for land preparation?
f115. If hired labour what was the Proportion?
f116. If family labour what was the Proportion?
f117. If voluntary, what was the proportion?
f118. State the Total cost for land preparation, state the currency
f119. Who was involved in land preparation?
f120. State the Total number of man hours used for family labour in land preparation
f121. State the Total number of man hours used for hired labour in land preparation
f122. State the man hours used for voluntary work during land preparation

Planting

f123. Which system of planting maize did you use?
f124. Which Method of planting maize did you use?
f125. When was the Time for planting maize?
f126. Who made decision on the time, type, when etc to plant maize?
f127. Which Kind of labour did you use for planting maize?
f128. If hired labour, what was the Proportion?
f129. If family labour, what was the Proportion?
f130. If voluntary, what was the proportion?
f131. State the Total cost of hired labour for planting. State the currency
f132. If family member, who was involved in planting
f133. State the Total number of man hours used for family labour for planting
f134. State the Total number of man hours used for hired labour for planting
f135. State the man hours used for voluntary work during planting
f136. State the Equipment that was used during planting

Planting costs

f137. Which type of Maize was used for planting in this plot?

f138. State the hybrid
f139. Which maize variety did you use for planting in this plot?
f140. State the Amount of seed used during planting, state the units
f141. Where did you acquire seed? (Source of seed)
f142. How easy or challenging was it to acquire seed? (Availability of maize seed)
f143. State the total cost of maize seed, state the currency

Intercrops planted

f144. State the Intercrop you planted on this plot?
f145. Which Intercrop variety did you use in this plot?
f146. State the time of planting the intercrop in this plot?
f147. Which Method did you use for planting intercrop in this plot?
f148. Who made the decision on the type, time to plant the intercrop?
f149. Which Kind of labour did you use for planting intercrop?
f150. If it was hired labour, what was the Proportion?
f151. If it was family labour, what was the Proportion?
f152. If it was voluntary labour, what was the proportion?
f153. State the Total cost of hired labour used for planting intercrop, state the currency
f154. If family labour, who was involved in planting intercrop
f155. State the Total man hours for family labour used during planting of intercrops
f156. State the Total man hours for hired labour used during planting of intercrops
f157. State the total man hours used for voluntary labour during planting of intercrops

Inorganic Fertilizer application

f158. Did you use inorganic fertilizer in this plot?
f159. How many times did you apply inorganic fertilizer in this plot?
f160. Fertilizer inorganic type 1
f161. At what stage of maize development was fertilizer application?
f162. At how many weeks from planting was fertilizer application done?
f163. What Quantity of fertilizer application did you use? State the unit
f164. What was the Cost of fertilizer? State the currency
f165. Who made Decision on the type, use, time and etc of fertilizer application?
f166. Which labour was used during fertilizer application?
f167. If hired labour indicate the Proportion
f168. If family labour indicate the Proportion
f169. If it was voluntary labour, what was the proportion?
f170. What was the Total cost of hired labour for fertilizer application? State the currency
f171. If family labour, who was involved 1
f172. State the Total man hours for fertilizer application for family labour during application
f173. State the Total man hours for fertilizer application for hired labour during application
f174. State the man hours used for voluntary labour during fertilizer application.

f175. Which equipment did you use?

Organic fertilizer application

f176. Did you use organic fertilizer?

f177. State the Number of applications

f178. Who made decision on when, time, usage and etc on organic fertilizer application?

f179. Which Type of organic fertilizer did you use?

f180. When was the application done?

f181. State the Quantity of application you used, state the local units

f182. Was the manure dry or wet?

f183. State the cost of organic fertilizer, if it was bought, state the currency

f184. State the Labour that was used

f185. If hired labour, indicate the Proportion

f186. If family labour, indicate the Proportion

f187. If voluntary, what was the proportion?

f188. State the Total cost of hired labour for organic fertilizer application, state the currency

f189. Who was involved in organic fertilizer application?

f190. State the Total man hours for family labour for fertilizer application

f191. State the Total man hours for hired labour for fertilizer application

f192. State the total man hours used for voluntary labour during fertilizer application

f193. Which equipment did you use?

f194. If no, give reason(s)

Weed control

f195. Did you practice weed control

f196. State the Number of times you did weed control

f197. Who made decision on the method, labour, time of weed control?

f198. Which Method of weed control did you use?

f199. At what stage of maize development was weed control done?

f200. After how many weeks from planting of maize was weed control done?

f201. Which Labour did you use for weed control?

f202. If hired labour was used indicate the Proportion

f203. If family labour was used indicate the Proportion

f204. If voluntary, what was the proportion?

f205. State the Total cost of hired labour for weed control, state the currency

f206. If family labour, who was involved?

f207. State the Total man hours used for family labour in weeding

f208. State the Total man hours used for hired labour for weeding in this plot

f209. State the total man hours used for voluntary labour during weed control

f210. If chemical application was used as a method of weed control, which herbicide did you use in this plot?

f211. State the amount of herbicide that was used in this plot, state the units

f212. Indicate the total cost that was used to purchase the herbicide in this plot, state the currency
f213. Equipment used for weed control
Irrigation method
f214. Did you practice irrigation?
f215. Who made the decision to irrigate the plot?
f216. When was the Time for irrigation?
f217. Which Irrigation method did you use?
f218. State the Water source
f219. Which Labour type did you use for irrigation?
f220. If hired labour, what was the Proportion?
f221. If family labour, indicate the Proportion?
f222. If Voluntary labour, what was the proportion?
f223. If family labour, who was involved?
f224. Equipment used during irrigation
f225. State the Total man hours for family labour used during irrigation
f226. State the Total man hours for hired labour used during irrigation
f227. State the total man hours used for voluntary labour during irrigation.
Harvesting
f228. Did you harvest any maize from this plot?
f229. State the quantity of maize harvested while green, state the units
f230. What quantity of matured dry maize was harvested? State the units
f231. Which labour was used?
f232. If hired labour, state the Proportion
f233. If family labour, state the Proportion
f234. If Voluntary labour, what was the proportion?
f235. Total man hours for family labour used during harvesting
f236. Total man hours for hired labour used during harvesting
f237. State the total man hours for voluntary labour used during harvesting
f238. If hired labour was used, indicate the total cost, state the currency
f239. On a scale of 1-3, with 1-Poor, 2-Average, 3-Good; rate the performance of the maize crop on this plot compared to the other plots
f240. Compare the harvest on this plot this year with last year; has it increased, decreased, or remained the same
f241. State the quantity of decrease or increase
f242. Give a reason for the decrease or increase
f243. If you didn't harvest any crop, give a reason
Crop Shocks
f244. Were there any shocks and disasters which could have affected productivity on this plot?
f245. If yes, state the type of shock
f246. At what stage of maize development did the shock occur?
Harvesting of intercrops
f247. Did you harvest any intercrops (beans, cowpeas etc) from this plot?

f248. Quantity harvested, state the units
f249. Which labour was used?
f250. Proportion of hired labour
f251. Proportion of family labour
f252. If voluntary, what was the proportion?
f253. Total man hours for family labour used during harvesting
f254. Total man hours for hired labour used during harvesting
f255. State the total man hours used for voluntary during harvesting
f256. If hired labour was used, what was the total cost? State the currency
f257. On a scale of 1-3, with 1-Poor 2-Average, 3-Good; rate the performance of the intercrop this plot
f258. Give a reason for your rating
f259. If no, give a reason

Soil and water control measures

f260. Have you planted any fodder crops on this plot?
f261. State the crops
f262. State the erosion control measures on this plot
f263. How do you utilize crop residue?

Credit facilitation

f264. Did you borrow loan or acquire any credit facilities for purchasing farm inputs or carrying out activities for this plot in this season?
f265. Who made decision to acquire credit?
f266. State the source of credit or loan
f267. State the amount of credit or loan borrowed
f268. Is this plot under One Acre Fund?
f269. Any comments?
f270. State your observation as the enumerator of the interview process
F271. Insert end time

Annex 3: Interview Guide for Photo-Elicitation Interviews

INTRODUCTION: [Greetings! This is a continuation of our study of your maize plots and data collected through field surveys and household surveys 2 years ago. Information collected in this interview will be handled with strict confidentiality and transcripts will be anonymized as much as possible to protect your privacy. You have the right to decline participation in the interview or withdraw your consent at any time in the course of the interview. You can also decline to provide responses to questions that you are not comfortable answering. We would like to audio record this conversation strictly for academic purposes, can we please go ahead?]

General

Village: ……………………………………………………………….

Name of farmer: ………………………………………………………………….

Farmer/plot ID: ………………………………………….

Specify the particular maize plot of interest. Verify that the interviewee carried out the day-to-day management of the particular maize plot. If not, get information and contact of the plot manager/operator and interview them instead.

What is the size of the maize farm in discussion (in acres)?

Plot Preparation Activities [The following questions pertain to only the major cropping season of March – August 2016 for the plot in question]

1. How do you prepare your land for planting? Why do you do it this way?
2. Has your land preparation method changed/remained the same over the past decade? Has your method of plot preparation improved the quality of your plot? How?
3. What farming implements do you use during plot preparations?
4. Did you use any modern farming implements (animal-hauled or fuel-powered tractors, knapsack sprayer, etc) during the land preparation of this plot?
5. What were the purposes for the usage of such modern implements? (level the ground, turn the soil, control weeds, etc)
6. How did you acquire these implements? (self-owned, rented, borrowed, etc). What is the duration of rental, cost of rental?
7. How easy is it to access such equipment? Did you get it when you needed/requested for it or you had to wait?
8. How many weeks/days before or after the first rains did you plough/till the plot? Why this timing?
9. Who decides how the land preparation is done, such as direction of ploughing, depth of tilling? [farmer, operator of the equipment, other family members]

Plot Management Activities

10. Planting: did you stagger planting or was the whole plot was planted at the same time? If planting was staggered, how far spread out (over how many weeks) was the planting period? Why?
11. Herbicide use: If yes, was this done on whole plot basis or site-specific application? Why this choice? How advantageous is the chemical method of weed control relative to other methods such as mechanical (using cutlass and hoe)?
12. Inorganic fertilizer application: If yes, did you undertake whole plot treatment or site-specific application? Why this approach? Did you have adequate quantities of fertilizer to apply?
13. At what stage of crop growth was the decision taken to apply fertilizers? Start of the season, or only when you estimated crops were not doing well enough? [*Ask only first part in an open way and leave the second part out and only give options to farmers if they appear uncertain*]
14. Was the quantity and type of fertilizer used influenced by the condition of the crops?

15. Did this plot experience any particularly destructive pest and disease infestation during that season? How did you deal with it?
16. What was the moisture/rainfall situation for the particular season?
17. What is your view on irrigation of your crops if a water source is available?
18. Generally, does the situation of the plot/crop conditions influence management activities or do activities planned take place nevertheless?

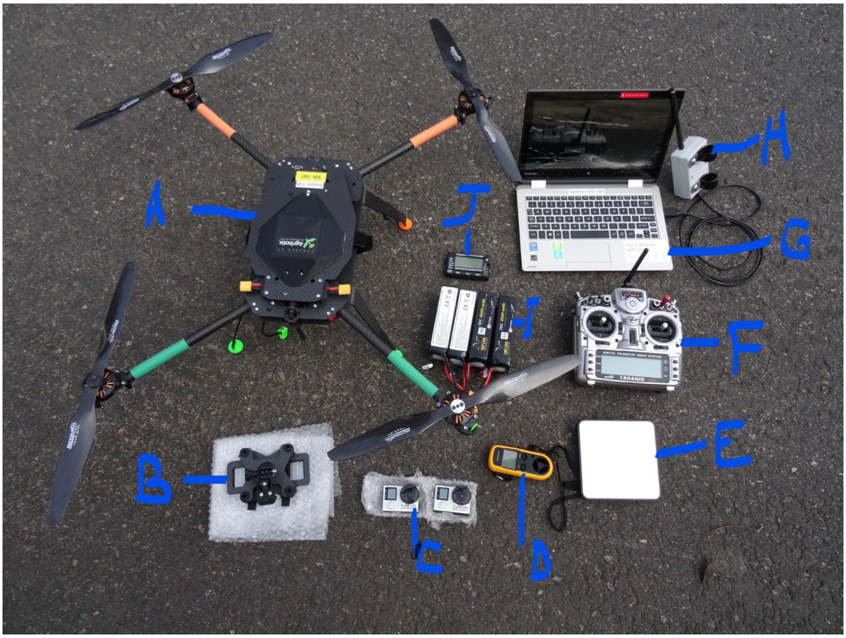
Co-Interpretation of Crop Health Maps

19. Based on your experience and knowledge of your plot from that season, would you agree with the depiction of the crop performance within your plot from the maps?
    19.1. Do yellow patches roughly correspond with your perception of poor patches based on your crop walks?
    19.2. Do greener areas also match healthier segments of your plots?
20. Why, in your estimation, are crops in the greener sections healthier relative to other areas?
    20.1. Are these factors naturally-occurring or management-induced?
    20.2. How can the growing conditions in the healthier sections of the plot be replicated in less vigorous areas?
21. What factors underlie the poor patches we see?
    21.1. Are they as a result of naturally-occurring factors or they are management-induced? How can the natural yield-inhibiting factors be remedied?
    21.2. How are you going to modify your management activities on this plot in future seasons to improve yields?
22. In your estimation, how does time of planting associate with crop vigour? [*Here, we want farmers to describe any possible association they discern between planting time and crop health*]
23. What do you think are the reasons for the generally poor crop health along the edges/borders of your plot?
    23.1. Did you attempt to deal with this situation in the course of the season? If yes, how? If no, why not?
24. If you had access to this crop health maps in the course of the season, would it have influenced how you managed your plot in terms of fertilizer/herbicide application? If yes, how? If no, why not?
25. Generally, how do you currently treat poor patches in your plot? [*Replacement planting of maize, plant other crops, ignore poor patches or continue to treat the whole plot uniformly in spite of the intra-plot variability?]*
    25.1. Why this approach?
26. Do you think you are getting adequate yields from your plot?
    26.1. Do you think the plot can yield much more than it is currently yielding?
    26.2. Is it worth your efforts and resources to invest in fertilizers, herbicides, irrigation, pesticides, and modern farming implements [knapsack sprayer, tractors, etc] on this plot?
    26.3. What factors inhibit the usage of these to boost yields?

27. Now, we have reached the conclusion of our conversation, are there any issues that you consider crucial to this conversation of the management of your plot that we have not discussed?

Thank you for your time!

Annex 4: The Unmanned Aerial Vehicle System



Component parts:
A – The Enduro Quadcopter with affixed propellers
B – Camera gimbal
C – Consumer-grade GoPro Hero 4 cameras
D – Digital anemometer
E – Calibration plates
F – Remote controller
G – A windows PC used as ground control station
H – Radio transmitter
I – LiPo Batteries

Annex 5: Description of informants for the PEIs

No.	Name*	Gender	Age**	Plot size (acres)	Plot productivity category	Role/profile
Village: Asitey						
1	TTH	Male	67	2	Below average	Farmer
2	CA	Female	63	1	Below average	Farmer
3	IP	Male	46	2	Below average	Farmer
4	JTN	Male	58	1.5	Below average	Farmer
5	ST	Female	54	1.5	Average	Farmer
6	KA	Male	57	0.8	Average	Farmer
7	NET	Male	59	2	Average	Farmer
8	KG	Male	55	0.5	Average	Farmer
9	KWM	Male	44	3	Above average	Farmer
10	KYT	Male	61	1.25	Above average	Farmer
11	AM	Male	36	2	Above average	Farmer
12	PNK	Male	57	2	Above average	VFC
13	LA	Male	-			DAO
Village: Akatawia						
14	AAA	Male	32	2	Below average	Farmer
15	EY	Female	34	2	Below average	Farmer
16	JOK	Male	50	1.2	Below average	Farmer
17	MNA	Female	48	1.5	Below average	Farmer
18	JK	Male	72	3	Average	Farmer
19	JT	Male	56	3.8	Average	Farmer
20	TKL	Male	60	1	Average	Farmer
21	KT	Male	55	2	Average	Farmer
22	SKT	Male	58	2	Above average	Farmer
23	TAT	Male	76	2	Above average	Farmer
24	TA	Male	42	1.2	Above average	Farmer
25	JTA	Male	60	3	Above average	VCF
26	AG	Male	-			DAO

NB: * Names of informants has been anonymised for privacy purposes. **Age of informant at the time of interviews. VCF = Village Chief Farmer and DAO = District Agriculture Officer.

A bird's-eye view of smallholder productivity

Achieving agricultural development through a sustainable growth in production and productivity is fundamental to dealing with the twin challenges of poverty and hunger in Sub-Saharan Africa countries. This is so because agriculture is dominated by smallholders who are relied upon to produce the bulk of the food needs of most of these countries. This thesis therefore aims to augment our present understanding of crop productivity levels on smallholder farms in resource-poor contexts. Ibrahim Wahab is a PhD Candidate at the Department of Human Geography, Lund University, Sweden. He is a geographer working at the intersection of smallholder agriculture, rural development and remote sensing and GIS applications in Sub-Saharan Africa. He completed his bachelors in Geography and Resource Development at the University of Ghana, Legon, Ghana and Master of Philosophy in Development Geography at the University of Oslo, Norway. This is his PhD thesis.

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